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Control of Robotic Systems in Contact Tasks

23.1 Introduction
23.2 Contact Tasks
23.3 Classification of Robotized Concepts for Constrained Motion Control
23.4 Model of Robot Performing Contact Tasks
23.5 Passive Compliance Methods
Nonadaptable Compliance Methods • Adaptable Compliance Methods
23.6 Active Compliant Motion Control Methods
Impedance Control • Hybrid Position/Force Control • Force/Impedance Control • Position/Force Control of Robots Interacting with Dynamic Environment
23.7 Contact Stability and Transition
23.8 Synthesis of Impedance Control at Higher Control Levels
Compliance C-Frame • Operating Modes • Change of Impedance Gains — Relax Function • Impedance Control Commands • Control Algorithms • Implicit Force Control Integration
23.9 Conclusion

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23.1 Introduction

This chapter reviews the state of the art of the control of compliant motion. It covers early ideas and later improvements, as well as new control concepts and recent trends. A comprehensive review of various compliant motion control methods proposed in the literature would certainly be voluminous, since the research in this area has grown rapidly in recent years. Therefore, for practical reasons, a limited number of the most relevant or representative investigations and methods are discussed. Before we review the results, we categorize compliant motion tasks and proposed control concepts based on various classifying criteria. Particular attention is paid to traditional indices of control performance and to the reliability and applicability of algorithms and control schemes in industrial robotic systems.

23.2 Contact Tasks

Robotic applications can be categorized in two classes based on the nature of interaction between a robot and its environment. The first one covers *noncontact*, e.g., unconstrained, motion in a free

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space, without environmental influence exerted on the robot. The robot's dynamics have a crucial influence upon its performance of noncontact tasks. A limited number of frequently performed simple robotic tasks such as pick-and-place, spray painting, gluing, and welding, belong to this group.

In contrast, many advanced robotic applications such as assembly and machining require the manipulator to be mechanically coupled to the other objects. In principle, two basic *contact task* subclasses can be distinguished. The first one includes *essential force tasks* whose nature requires the end effector to establish physical contact with the environment and exert a process-specific force. In general, these tasks require the positions of the end effector and the interaction force to be simultaneously controlled. Typical examples of such tasks are machining processes such as grinding, deburring, polishing, and bending. Force is an inherent part of the process and plays a decisive role in task fulfillment (e.g., metal cutting or plastic deformation). In order to prevent overloading or damage to the tool during operation, this force must be controlled in accordance with some definite task requirements.

The prime emphasis within the second subclass lies on the requirement for end effector motion near the constrained surfaces (*compliant motion*). A typical representative task is the part mating process. The problem of controlling the robot during these tasks is, in principle, the problem of accurate positioning. However, due to imperfections inherent in the process and the sensing and control system, these tasks are inevitably accompanied by contact with constrained surfaces, which produces reaction forces. The measurement of interaction force provides useful information for error detection and allows appropriate modification of the prescribed robot motion.

Future research will certainly develop more tasks for which interaction with the environment will be fundamental. Recent medical robot applications (e.g., spine surgery, neurosurgical and microsurgical operations, and knee and hip joint replacements) may also be considered *essential contact tasks*. Comprehensive research programs in automated construction, agriculture, and food industry focus on the robotization of other types of contact tasks such as underground excavation and meat deboning.

Common to all contact tasks is the presence of the constraints upon robot motion due to environmental objects. If all parameters of the environment and robot were known and robot positioning was precise, it might be possible to accomplish the majority of these tasks using the same control strategies and techniques developed for the control of robot motion in free space. However, none of these conditions can be fulfilled in reality. Hence, contact tasks are characterized by the dynamic interaction between robot and environment, which often cannot be predicted accurately. The magnitude of the mechanical work exchanged between the robot and the environment during contact may vary drastically and cause significant alteration of performance of the robotic control system. Therefore, for successful completion of contact tasks, the interaction forces have to be monitored and controlled, or control concepts ensuring the robot interacts compliantly with the environment must be applied.

Compliance, i.e., accommodation,[1] can be considered a measure of the ability of a manipulator to react to interaction forces. This term refers to a variety of control methods in which the end effector motion is modified by contact forces.

23.3 Classification of Robotized Concepts for Constrained Motion Control

The previous classification of elementary robotic tasks provides a framework for the further systematization of compliant motion control. Recently, the problems encountered in the control of compliant motion have been extensively investigated and several control strategies and schemes have been proposed. These methods can be systematized according to different criteria. The primary systematization requires considering the kind of compliance. According to this criterion, two basic groups of control concepts for compliant motion are distinguishable (Figure 23.1):

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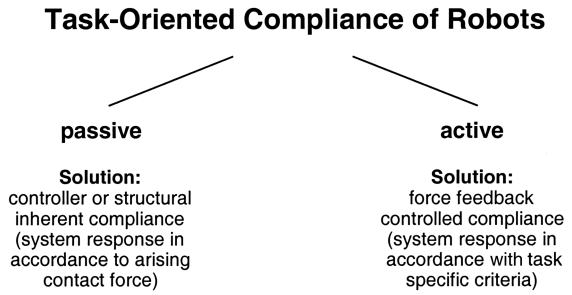

FIGURE 23.1 Basic classification of robot compliance.

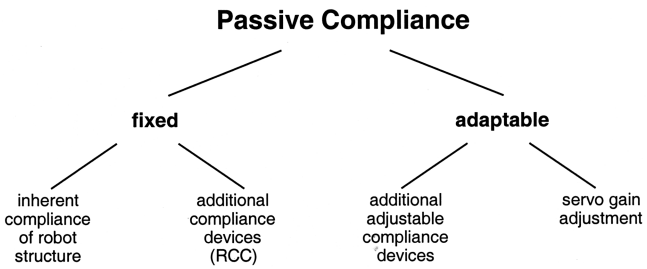

FIGURE 23.2 Passive compliance classification.

1. *Passive compliance,* whereby the position of the end effector is accommodated by the contact forces due to compliance inherent in the manipulator structure, servos, or special compliant devices.
2. *Active compliance,* whereby the compliance is provided by constructing a force feedback in order to achieve a programmable robot reaction, either by controlling interaction force* or by generating task-specific compliance at the robot end point.

Regarding the possibility of adjusting system compliance to specific process requirements, passive compliance methods can be categorized as *adaptable* and *nonadaptable*. Based on the dominant sources of compliance, two methods within these groups can be distinguished (Figure 23.2):

1. Fixed (or nonadaptable) passive compliance:
   a. Methods based on the inherent compliance of the robot's mechanical structure, such as elasticity of the arm, joints, and end effectors.[2]
   b. Methods that use specially constructed passive deformable structures attached near the end effectors and designed for particular problems. The best known is the remote center compliance (RCC) element.[3]
2. Adaptable passive compliance:
   a. Methods based on devices with tunable compliance.[4]
   b. Compliance achieved by the adjustment of joint servo-gains.[5]

The basic classification of *active compliance* control methods is based on the classifying tasks as *essential* or *potential*. Using the terminology of bond–graph formalisms, robot behavior that performs *essential contact tasks* can be generalized as a source of *effort* (force) that should raise

*By *force* we mean *force and torque* and, accordingly, *position* should be interpreted as *position and orientation.*

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a *flow* (motion) reaction by environmental objects. The robot behavior associated with the second or *potential* subclass corresponds to *impedance,* characterized by the reaction of robot's motion on external forces exerted by the environment. The active control force method can be classified into two groups:

1. *Force*, i.e., *position/force control* or *admittance control*, whereby both desired interaction force and robot position are controlled. A desired force trajectory is commanded and force measurements are required to realize feedback control.
2. *Impedance control,*[6] uses the different relationships between acting forces and manipulator position to adjust the mechanical impedance of the end effector to external forces. Impedance control can be defined as allowing interaction forces to govern the error between the nominal and actual positions of the end effector according to the target impedance law. Impedance control is based on position control and requires position commands and measurements to close the feedback loop. Force measurements are needed to effect the target impedance behavior.

Position/force control methods can be divided into two categories:

1. *Hybrid position/force control*, whereby position and force are controlled in a nonconflicting way in two orthogonal subspaces defined in a task-specific frame (*compliance* or *constraint frame*). For force-controlled end-effector degrees of freedom (DOF), the contact force is essential for performing the task. The motion is most important in position DOF. Force is commanded and controlled along directions constrained by the environment, while position is controlled in directions in which the manipulator is free to move (*unconstrained*). *Hybrid control* is usually referred to as the method of Raibert and Craig.[7] However, according to Mason's[1] definition, this term is used in a more general sense and is defined as any controller based on the division into force and position controlled directions.
2. *Unified position/force control,* which differs essentially from the above conventional hybrid control schemes.Vukobratović and Ekalo[8,33] have established a dynamic approach to simultaneously control both the position and force in an environment with completely dynamic reactions. The approach of dynamic interction control[8,33] defines two control subtasks responsible for stabilization of robot position and interaction force. Both control subtasks utilize a dynamic model of the robot and the environment in order to ensure the tracking of the nominal motion and the force.
3. *Parallel position-force control,*[9] is based on the appropriate tuning of the position and force controllers. The force loop is designed to dominate the position control loop along constrained task directions where a force interaction is expected. From this viewpoint, the parallel control can be considered as impedance/force control.

Taking into account the way in which the force information is included in the forward control path, the following position/force control schemes can further be distinguished:

1. *Explicit* or *force-based*[7,10,11] whereby force control signals (i.e., the difference between the desired and actual forces) are used to generate the torque inputs for the actuators in the joints.
2. *Implicit* or *position-based* algorithms[12,13] whereby the force control error is converted to an appropriate motion adjustment in force-controlled directions and then added to the positional control loop.

Impedance control methods can also be distinguished by the way the robotic mechanism is treated: either as an actuator (i.e., source) of position or as an actuator of a force. The aim in impedance control is to provide specific relationships between effort and motion rather than follow a prescribed force trajectory as in the case of force control. Considering the arrangement of position and force sensor and control signals within control loops (inner or outer), the following two common approaches to provide task-specific impedance via feedback control can be distinguished:[14]

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1. *Position mode* or *outer loop control,* whereby a target impedance control block relating the force exerted on the end effector and its relative position is added within an additional control loop around the position-controlled manipulator. An inner loop is closed based on the position sensor and an outer loop is closed around it based on the force sensor.[15,16]
2. *Force mode* or *inner loop* control, whereby position is measured and force command is computed to satisfy target impedance objectives.[14]

Regarding the force–motion relationship or the impedance order, impedance control schemes can be further categorized into: *stiffness control,*[17] *damping control*,[18] and *general impedance control,*[19,20] using zeroth, first, and second order impedance models respectively.

There are additional criteria that allow further classification of active compliant motion control concepts. For example, we can distinguish the methods with respect to the *source of force information* (with or without direct interaction force sensing), and the *allocation of force sensor* (wrist, torque sensor in joints, force-sensing pedestal, force sensor at the contact surface, sensors at robot links, fingers, etc.). To avoid the problems associated with noncollocation between measurement of contact forces and actuation in robot joints, which can cause instability,[21] the use of redundant force information combining joint force sensing with one of the above force sensing principles was proposed.

Regarding the space in which the active force control is performed in, one can distinguish between two methods:

1. *Operational space control* techniques where control takes place in the same frame in which actions are specified.[22,23] This approach requires the construction of a model describing the system dynamic behavior as perceived at the end effector where the task is specified (operational point, i.e., coordinate frame). The traditional approach for specifying compliant motion uses a *task* or *compliance frame* approach.[1] This geometrical approach introduces a Cartesian-compliant frame with orthogonal force and position (velocity)-controlled directions. To overcome the limitations of this approach, new methods were proposed.[24,25] These approaches, referred to as *explicit task specification of compliant motion*, are based on the model of the constraint topology for every contact configuration and utilize projective geometry metrics to define a hybrid contact task.
2. *Joint space control*, whereby control objectives and actions are mapped into joint space.[26] Associated with this control approach are transformations of action attributes, compliance, and contact forces from the task into the joint space.

Further, considering control issues, such as variations of control parameters (gains) during execution, one can distinguish:

1. *Nonadaptive* active compliance control algorithms that use fixed gains assuming small variations in the robot *and* environment parameters
2. *Adaptive control*, which can adapt the variation of process[27,28]
3. *Robust control* approaches, which maintain model imprecision and parametric uncertainties within specified bounds[29,30]

Depending on the extent to which system dynamics is involved in the applied control laws, it is possible to further distinguish:

1. *Nondynamic*, i.e., *kinematic model-based* algorithms, such as *hybrid control*,[7] *stiffness control,*[17] etc., which approximate the contact problem considering its static aspects only.
2. *Dynamic model-based* control schemes, such as *resolved acceleration control,*[31] *dynamic hybrid control,*[11] *constrained robot control,*[32] and *dynamic force-position control in contact with dynamic environment,*[8,33] based on complete dynamic models of the robot and the environment that take into account all dynamic interactions between position- and force-controlled directions.

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Although contact motion is characterized by relatively low velocities, high dynamic interaction (i.e., exchange of energy) between a robot and its environment affects the control system significantly and can jeopardize the stability of the control system.[34] Consequently, the role of both dynamics, namely dynamics of the robot[35] and dynamics of the environment,[8,33] in the control of compliant motion, becomes essential. Kinematic algorithms are mostly based on Jacobian matrix computation, while the complexity of the dynamic methods is much greater.[36]

The seminal hybrid control method proposed by Raibert and Craig[7] essentially provides a quasistatic approach to compliance control based on an idealized simple geometric model of a constrained motion task (Mason's *constraint frame formalism*). With hybrid control, the dynamics of both robot and environment (dynamic interaction) is neglected. The *dynamic hybrid control*[11] and *constrained motion control*[32] approaches consider the constraints upon robot motion in the form of algebraic equations defining a hyper surface. These methods take the robot dynamic model and the model of the environment into account in order to synthesize dynamic control laws to ensure admissible robot motion with the constraint and achieve desired interaction forces. Generalization of the constrained motion problem leads to introducing active dynamic contact forces (dynamic environment), also described by differential equations. In a dynamic environment, the interaction forces are not compensated by constraint reactions; they produce active work on the environment. Obviously, contact with a dynamic environment requires consideration of the complete system dynamics involving robot and interaction models to obtain admissible robot motion and interaction forces. The "pure dynamic" interaction without passive reaction was considered by Vukobratović and Ekalo in papers dedicated to the dynamic control of robots interacting with the dynamic environment.[8,33,89–91] A suitable model structure has been proposed by De Luca and Manes[37] that handles a most general case in which purely kinematic constraints on the robot end-effector live together with the dynamic interactions.

Although very inclusive, the above classification cannot encompass all of the proposed concepts to date. Some approaches combine two or more methods categorized in distinct groups, and attempt to use the benefits of both to offset disadvantages of single solution strategies. Such methods use compliant motion control approaches that combine force and impedance control.[12,38] Some methods integrate control mechanical system design.[39] This approach is based on *micro–macro* manipulator structures that provide inherently stable and well-suited subsystems for high bandwidth active force control.

The terminology used above represents, in some measure, a trade-off among different nomenclatures used in the literature. Mason[1] designates the control concepts by specifying the linear relation between effector force and position as *explicit feedback*, while Whitney[6] uses the phrase *explicit control* to refer to techniques having a desired force input other than position or velocity input. The classification and the terminology reflect, in our opinion, the essential aspects of appropriate control strategies. The above classification is summarized in Figures 23.1 through 23.3.

23.4 Model of Robot Performing Contact Tasks

During the execution of a contact task, the kinematic structure of the robot changes from an open to a closed chain. Contact with the environment imposes kinematic and dynamic constraints on the motion of the end effector. One of the most difficult aspects of dynamic modeling concerns the interactions of bodies in contact. We will briefly consider simplified models of constrained motion to be used for the analysis of contact motion control concepts.

In order to form a mathematical model that describes the dynamics of the closed configuration manipulator, let us consider an open robot structure whose last link (end effector) is subjected to a generalized external force (Figure 23.4). A dynamics model of rigid manipulation robot interacting with the environment is described by the vector differential equation in the form:

$$\mathbf{H}(\mathbf{q})\ddot{\mathbf{q}} + \mathbf{h}(\mathbf{q}, \dot{\mathbf{q}}) + \mathbf{g}(\mathbf{q}) = \boldsymbol{\tau}_a + \mathbf{J}^T(\mathbf{q})\mathbf{F} \tag{23.1}$$

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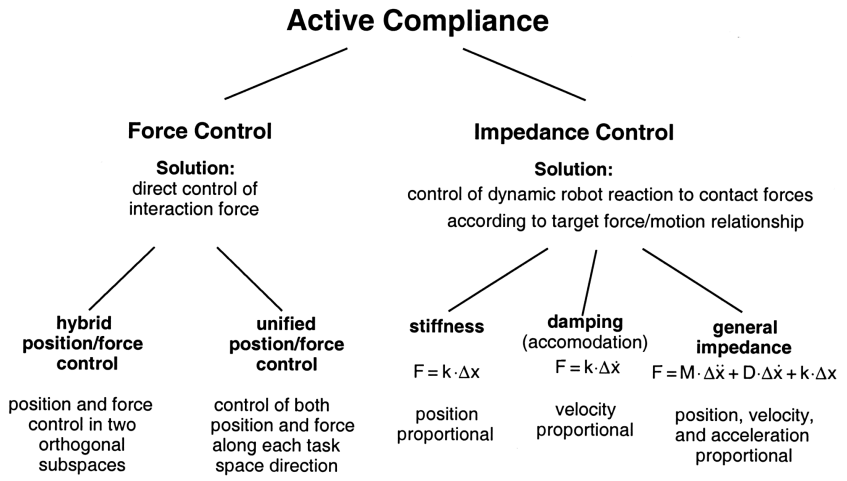

FIGURE 23.3 Active compliance control methods.

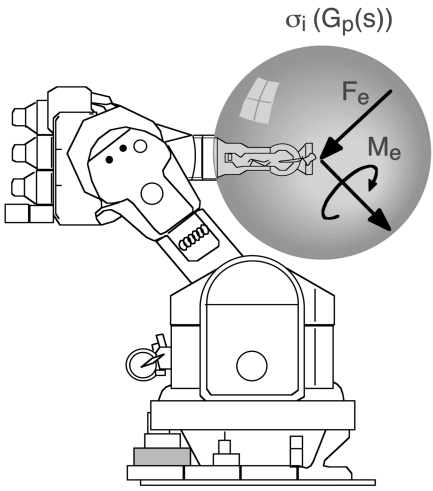

FIGURE 23.4 Open kinematic chain exposed to an external force action.

where $\mathbf{q} = \mathbf{q}(t)$ is an n-dimensional vector of robot generalized coordinates; $\mathbf{H}(\mathrm{q})$ is an $n \times n$ positive definite matrix of inertia moments of the manipulator mechanism; $\mathbf{h}(\mathrm{q}, \dot{\mathrm{q}})$ is an n-dimensional nonlinear function of centrifugal and Coriolis moments; $\mathbf{g}(\mathrm{q})$ is a vector of gravitational moments; $\boldsymbol{\tau}_a = \boldsymbol{\tau}_a(t)$ is an n-dimensional vector of generalized joint axes driving torques; $\mathbf{J}(\mathrm{q})$ is an $n \times m$ Jacobian matrix relating joint space velocity to task space velocity; and $\mathbf{F} = \mathbf{F}(t)$ is an m-dimensional vector of external forces and moments acting on the end effector.

The dynamic model of the actuator (we confine discussion to robot manipulators driven by DC motors) that drive the robot joints must be added to the above equations. It is convenient to adopt this model in linear form. Taking into account that electric time constants of DC motors driving almost all commercial robotic systems are very low, we shall adopt a second order model of actuators:

$$n_i^2 I_{mi} \ddot{q}_{mi} + n_i^2 b_{mi} \dot{q}_{mi} + \tau_{ai} = n_i \tau_{mi} \tag{23.2}$$

where q_{mi} is the output angle of the motor shaft after-reducer; n_i is the gear ratio; I_{mi} is the inertia of the motor actuator; b_{mi} is the viscous friction coefficient; τ_{mi} is the control input to the i-th

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actuator (i.e., motor torque); and where i denotes the local i-th subsystem. The torque produced by the motor is proportional to the armature current, that is:

$$\tau_{mi} = k_{mi} i_{mi} \tag{23.3}$$

where k_{mi} is the torque constant. If we assume the stiffness in the joints (gears) to be infinite, the relation between the coordinate of the mechanism q_i coincides with the actuator coordinate q_{mi}.

The dynamic models of the actuators and mechanical parts of the robot are related by joint torques (loads). If we substitute τ_{ai} from (23.2) into (23.1) we get the entire model of the robotic mechanism in joint coordinate space:

$$\overline{\mathbf{H}}(\mathrm{q})\ddot{\mathbf{q}} + \mathbf{B}_m \dot{\mathbf{q}} + \mathbf{h}(\mathrm{q}, \dot{\mathrm{q}}) + \mathbf{g}(\mathrm{q}) = \boldsymbol{\tau}_{\mathrm{q}} + \mathbf{J}(\mathrm{q})^T \mathbf{F} \tag{23.4}$$

where:

$$\overline{\mathbf{H}}(\mathrm{q}) = \mathbf{H}(\mathrm{q}) + \mathbf{I}_m = \mathbf{H}(\mathrm{q}) + diag(n_i^2 I_{m_i})$$

$$\mathbf{B}_m = diag(n_i^2 b_{mi}) \tag{23.5}$$

and $\boldsymbol{\tau}_q$ is 6×1 vector of input torques at the joint shaft (after-reducer):

$$\boldsymbol{\tau}_{\mathbf{q}} = \left[n_1 \tau_{m1} .... n_6 \tau_{m6} \right]^T.$$

The above dynamical model can be transformed into an equivalent form that is more convenient for analysis and synthesis of a robot controller for contact tasks. When the manipulator interacts with the environment, it is convenient to describe its dynamics in the space where manipulation task is described, rather than in joint coordinate space (also termed *configuration space*). The end effector position and orientation with respect to a reference coordinate system can be described by a six-dimensional vector **x**. The reference system is chosen to suit a particular robot application. Most frequently, a fixed coordinate frame attached to the manipulator base is considered as the reference system. Using the Jacobian matrix, we can transform the dynamic models (23.4) from the joint into the end effector coordinate system:

$$\boldsymbol{\Lambda}(x)\ddot{\mathbf{x}} + \mathbf{B}(x)\dot{\mathbf{x}} + \boldsymbol{\mu}(x, \dot{x}) + \mathbf{p}(x) = \boldsymbol{\tau} + \mathbf{F} \tag{23.6}$$

where relationships among corresponding matrices and vectors from Equations (23.1) and (23.6) are given by the following equations:

$$\begin{aligned}
\boldsymbol{\Lambda}(x) &= \mathbf{J}(q)^{-T} \mathbf{H}(\mathbf{q}) \mathbf{J}(q)^{-1} \\
\mathbf{B}(x) &= \mathbf{J}(\mathbf{q})^{-T} \mathbf{B}_{\mathbf{m}} \mathbf{J}(\mathbf{q})^{-1} \\
\boldsymbol{\mu}(x, \dot{x}) &= \mathbf{J}(q)^{-T} \mathbf{h}(q, \dot{q}) - \boldsymbol{\Lambda}(x) \dot{\mathbf{J}}(q, \dot{q}) \dot{\mathbf{q}} \\
\mathbf{p}(x) &= \mathbf{J}(q)^{-T} \mathbf{g}(\mathrm{q}) \\
\boldsymbol{\tau} &= \mathbf{J}(q)^{-T} \boldsymbol{\tau}_{\mathbf{q}}
\end{aligned} \tag{23.7}$$

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The description, analysis, and control of manipulator systems with respect to the dynamic characteristics of their end effectors are referred to as the *operational space formulation*.[22] Analogous to the joint space quantities, $\mathbf{\Lambda}(x)$ is the operational space inertia matrix, $\boldsymbol{\mu}(x,\dot{x})$ is the vector of Coriolis and centrifugal forces, $\mathbf{p}(x)$ is the vector of gravity terms, and $\boldsymbol{\tau}$ is the applied input control force in the operational space.

The interaction force is influenced by robot motion and also by the nature of the environment. Since mechanical interaction is generally very complex and difficult describe mathematically, we are compelled to introduce certain simplifications and thus partly idealize the problem. In practice, the interaction force **F** is commonly modeled as a function of the robot dynamics, i.e., end-effector motion (position, velocity, and acceleration) and control input:

$$\mathbf{F} = \mathbf{F}\left(\mathbf{x}, \dot{\mathbf{x}}, \ddot{\mathbf{x}}, \boldsymbol{\tau}, \mathbf{d}, \mathbf{d}_e\right) \tag{23.8}$$

where $\mathbf{d}$ and $\mathbf{d}_e$ denote sets of robot and environment model parameters, respectively. The following general work environment models have been mostly applied in the literature for describing constrained motion: *rigid hypersurface*, *dynamic environment*, and *compliant environment*.

In contact with a rigid hypersurface, robot motion (i.e., surface penetration) is prevented in the direction orthogonal to the surface. For maintaining the constraint, only an infinitesimal displacement in the tangential hyperplane is allowed. Different models describing robot constrained motion on a rigid hypersurface have been presented in Yoshikawa et al.[11] and McClamroch and Wang.[32] These models can be applied for simulation or control design, i.e., computation of control laws ensuring the robot remains on the constraint manifold. However, the complexity of these models is great. In the special case of a rigid plane, model decomposition is relatively simple and does not require that computations are repeated for every step. In general, however, computing and integrating these models involves extensive computations and solutions of numerical problems.

If the environment does not possess displacements (DOFs) independent of the robot motion, the mathematical model of the environment dynamics in the frame of robot coordinates can be described by nonlinear differential equations:[8]

$$\mathbf{M}(\mathrm{q})\ddot{\mathbf{q}} + \mathbf{L}(\mathrm{q}, \dot{\mathrm{q}}) = -\mathbf{S}^{\mathbf{T}}(\mathrm{q})\mathbf{F} \tag{23.9}$$

where $\mathbf{M}(\mathrm{q})$ is a nonsingular $n \times n$ matrix; $\mathbf{L}(\mathrm{q}, \dot{\mathrm{q}})$ is a nonlinear n-dimensional vector function; and $\mathbf{S}^{\mathbf{T}}(\mathrm{q})$ is an $n \times n$ matrix with rank equal to n. The system (23.4-23.9) then describes the dynamics of robot interaction with dynamic environment. We assume that all the mentioned matrices and vectors are continuous functions of the arguments for the contact cases.

In operational space, the model of a pure dynamic environment has the form:[40]

$$\boldsymbol{M}(\mathrm{x})\ddot{\mathbf{x}} + \mathbf{l}(\mathrm{x}, \dot{\mathrm{x}}) = -\mathbf{F}$$

$$\boldsymbol{M}(\mathrm{x}) = \mathbf{J}(q)^{-T}\mathbf{M}(q)\mathbf{J}(q)^{-1}$$

$$\mathbf{l}(\mathrm{x}, \dot{\mathrm{x}}) = \mathbf{J}(q)^{-T}\mathbf{L}(q, \dot{q}) - \boldsymbol{M}(\mathrm{x})\dot{\mathbf{J}}(q)\dot{\mathbf{q}}$$

In effect, a general environment model involves geometrical (kinematic) constraints plus dynamic constraints.[37] An example of such a dynamic environment is when a robot is turning a crank or sliding a drawer. Dynamics is relevant for the robot motion and cannot be neglected. However, the dynamic model of kinematic–dynamic constraints is rather complex and its computation involves several difficulties. The crucial problem is the decomposition of DOFs, i.e., force and independent coordinate parameterization, which is not unique from a mathematical viewpoint. Although in several elemental contact cases, the feasible model parameterization is

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obvious,[37] it is difficult to perform model parameterization in many practical contact tasks. Planning and computing tools supporting automatic minimal parameterization of a dynamic constrained motion problem based on task specification do not exist. Moreover, the differentiation of constraint equations can lead to unstable numerical solutions, causing constraint violation in real-time simulations. By introducing inaccuracy in the robot and environment (e.g., for robust control design purposes), the problem becomes even more complicated.

For control design purposes, it is customary to utilize a linearized model of manipulator and environment. The applicability of a linearized model in constrained motion control design, especially in industrial robotic systems, was demonstrated in Goldenberg[41] and Šurdilović.[42] Neglecting nonlinear Coriolis and centrifugal effects due to relatively low operating velocities (rate linearization) during contact, and assuming the gravitational effect to be ideally compensated for, we obtain a linearized model around a nominal trajectory in Cartesian space $\mathbf{x}_0$ in the form:

$$\mathbf{\Lambda}(x_0)\ddot{\mathbf{x}} + \mathbf{B}(x_0)\dot{\mathbf{x}} = \boldsymbol{\tau}(\mathbf{x_0}) + \mathbf{F} \tag{23.10}$$

In passive linear environments, it is convenient to adopt the relationship between forces and motion around the contact point in the form (*linear elastic environment*):

$$-\mathbf{F} = \mathbf{M}_e\ddot{\mathbf{p}} + \mathbf{B}_e\dot{\mathbf{p}} + \mathbf{K}_e\mathbf{p} \tag{23.11}$$

where $\mathbf{p}$ denotes the end effector *penetration* through the surface defined by $\mathbf{p} = \mathbf{x} - \mathbf{x}_e$, $\mathbf{x}_e$ represents contact point locations, and $\mathbf{M}_e$, $\mathbf{B}_e$, and $\mathbf{K}_e$ are inertial, damping, and stiffness matrices, respectively.

23.5 Passive Compliance Methods

According to the classifications presented above, we first review the compliant control methods based on passive accommodation (with no actuator involved). *Passive compliance* is a concept often used to overcome the problems arising from positional and angular misalignments between the manipulator and its working environment.

23.5.1 Nonadaptable Compliance Methods

The passive compliance method, which is based on *inherent robot structural elasticity,* is more interesting as a theoretical solution than a feasible approach. This method assumes that the compliance of the mechanical structure has a determining effect on the compliance of the entire system. However, this assumption is opposite to the real performance of commercial robotic systems which are designed to achieve high positioning accuracy. Elastic properties of the arms are insignificant. The dominant influence on a somewhat larger deflexion of the manipulator tip position is, in some cases, joint compliance, e.g., due to reducer elasticity (harmonic drive) or compressibility of the hydraulic actuator.[43] In practice, the mechanical compliance of the robotic structure can be utilized for contact tasks purposes under very restricted conditions. The endpoint compliance is often unknown and too complex to be modeled. Due to high stiffness levels, the accommodation range within an acceptable contact force level is usually extremely small and without any practical values. This method does not offer any possibility to adapt system compliance to the various task requirements. The idea of utilizing flexible manipulator arms as an instrumented compliant system[2] is relatively new and poses additional problems due to complex modeling and controlling of elastic robots.

The method based on *mechanical compliance devices*, in principle, also utilizes structural compliance. The most influential source of multi-axis compliance in this case, however, is a specially constructed device whose behavior is known and sufficiently repeatable. Relatively good performances have been achieved, especially in the robotic assembly. Different types of such devices

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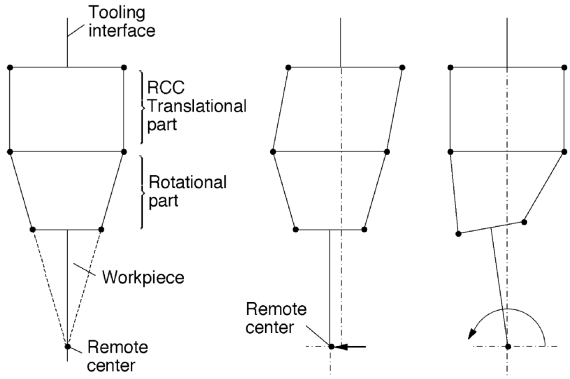

FIGURE 23.5 Remote center compliance (RCC).

have been developed; the best known is the RCC (remote center compliance)[3] developed in the Charles Stark Draper Laboratory. RCC is designed to make the workpiece rotate around a defined center of compliance. The compliance center is a point at which application of a force causes only translation, while a torque applied around an axis through this point will cause rotation of the workpiece (Figure 23.5). A crucial feature of the RCC is that it consists of translational and rotational parts; this combination allows lateral and angular errors to be accommodated independently.

RCC elements provide a simple and effective solution that permits fast and easy interfacing of mechanical parts in spite of initial positioning errors. The main advantage is that a simple positional controller can be applied, without any additional force sensor feedback or complex calculations. However, an RCC element cannot be applied to tasks involving parts of lengths and weights. A solution to this problem may be to design a set of compliance adapters that can be changed according to the needs of specific tasks.

Instrumented Remote Center Compliance (IRCC)[44] represents an improvement of RCC which provides the fast error absorption characteristic of RCC and the measurement characteristic of a multi-DOF sensor. Contact force and deformation data can be used for task monitoring, calibration, contour following, or positioning feedback.

23.5.2 Adaptable Compliance Methods

Further development of RCC has led to *adaptable compliant devices*[4] which enable the location of the center of compliance to be automatically controlled to a prescribed extent in accordance with parts of different lengths and weights. These devices are usually also instrumented to provide information about end point deflections for robot control.

The *controller gain adjustment method* is based on the compliance of the robotic controller and attempts to provide a universally programmable passive compliance at endpoints, by the relatively simple adjustment of servo gains. The basic principle is to tune the positional servo gains to make the robot behave as a linear six-dimensional spring in Cartesian space with programmable stiffness. Therefore, taking into account the relationship between forces exerted upon the robot and its reaction (stiffness-like behavior), the gain adjustment method was considered equivalent to the impedance (i.e., stiffness) control.

The choice of Cartesian stiffness matrix is strongly dependent on the task specification. In the case of part mating, for example, the elements of the stiffness matrix that relate force and motion in the direction of insertion should be estimated sufficiently high so that axial force does not cause the insertion to stop. Conversely, in lateral directions, the corresponding elements should be sufficiently low to enable the peg to move easily as it encounters the chamfer. A strategy for systematic setting of Cartesian stiffness in different phases of peg/hole assembly is proposed by Simons and Van Brussel.[5]

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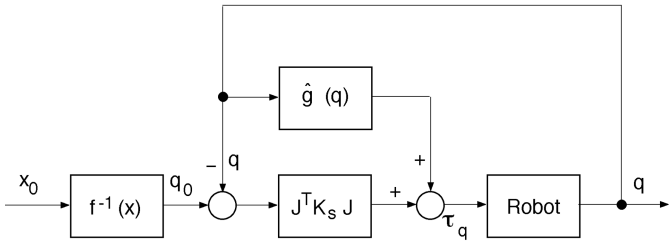

FIGURE 23.6 Passive gain adjustment scheme.

The basic gain adjustment control scheme is sketched in (Figure 23.6), where $\mathbf{x}^0$ and $\mathbf{q}^0$ are nominal Cartesian and joint position vectors, respectively; $\mathbf{f}^{-1}(\mathbf{x})$ denotes the inverse kinematic transformation; $\mathbf{q}$ is the actual joint position; and $\hat{\mathbf{g}}(q)$ is the computed gravitational torque. The control torque $\boldsymbol{\tau}_q$ is obtained according to:

$$\boldsymbol{\tau}_q = \mathbf{k}_p(\mathbf{q}_0 - \mathbf{q}) + \hat{\mathbf{g}}(q) \tag{23.12}$$

where $\mathbf{k}_p$ represents the joint stiffness matrix which should be tuned to ensure the arm will behave with the desired stiffness $\mathbf{K}_S$. The relationship between the joint and Cartesian stiffness matrices is given by:

$$\begin{aligned} \mathbf{k}_p &= \mathbf{J}^T \mathbf{K}_S \mathbf{J} \\ \mathbf{K}_S &= \mathbf{J}^{-T} \mathbf{k}_p \mathbf{J}^{-1} \end{aligned} \tag{23.13}$$

where $\mathbf{J}(q)$ represents Jacobian matrix-relating velocities (i.e., forces) between a Cartesian frame attached at the compliance center and the joint coordinate space. At the center of compliance, the Cartesian stiffness matrix is diagonal, but corresponding joint stiffness $\mathbf{k}_P$ is, according to Equation (23.13), a fully symmetric matrix. This means that the joint stiffness matrix is highly coupled and a position error in one joint will affect the commanded torque in all other joints.

Equation (23.12) represents the central formulation of active gain adjustment methods. Assuming the static (gravitational) forces are exactly compensated for and dynamic forces due to slow displacements are negligible, it is relatively easy to prove that the linearized robot-and-environment model is always stable. Control adjustment allows us to adopt the location of center of compliance (by the aid of Jacobian matrix $\mathbf{J}$) and Cartesian stiffness (choosing $\mathbf{K}_S$). However, although this stiffness-like behavior could be theoretically adjusted on-line while running a task, we have classified this method as passive compliance, because the compliant motion is performed in a purely passive way by the action of external forces, rather than by force feedback as with active stiffness control.

While the adaptable passive compliance method provides a simple and flexible solution for many compliant motion tasks (without requirements for force sensing and feedback), the aim of having the entire robot structure behave loosely in some directions is difficult to achieve. This concept is coupled with several problems. Most contemporary robotic systems cannot accurately achieve the desired spring-like behavior. Several nonlinearities such as friction and backlash in mechanical transmission and process frictional phenomena like jamming can destroy the stiffness force/position causality. Furthermore, by setting very low control gains in some directions, the entire system is made more sensitive to perturbations. Different disturbances and nonlinearities can affect performance, and that can be extremely dangerous in some environments. Since integral control action is not applied, all static effects such as gravitation must be completely compensated for.

All these factors make the performance of this control approach uncertain, thus imposing the need to introduce additional sensor information to monitor task execution. Relevant improvements

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can be achieved by including force sensor information in a rule-based assembly strategy,[5] or by introducing an internal force feedback loop.[45] However, the simplicity of passive gain adjustment is lost when these additional strategies are applied. An equivalent improvement in performance can be achieved by applying a simple active force control concept.

The principle of adaptable control gains is more suitable for direct drive, multifingered, or wrist hands. This method appears similar to those described above, which use special adaptable compliant devices.

If the passive gain adjustment concept is used in industrial practice, one should consider that conventional robotic systems are *nonbackdriveable* due to high gear ratios and Coulomb friction/stiction effects in joints. (The order of equivalent friction force in Cartesian space is about 10^2 N.) Hence, although compliant control is applied, a force exerted at the end effector will not cause a corresponding detectable displacement in joints. Therefore, the method can be applied only in manipulation tasks that permit large interaction forces. Due to relatively high costs and low robustness of force sensors, though, there is increased interest on the part of industrial robot manufacturers in appling this method in specific tasks such as handling of castings (e.g., the new *soft servo* or *soft float* industrial robot control functions).

23.6 Active Compliant Motion Control Methods

The active compliance control methods best utilize reprogrammability of manipulation robots. This is done by representing the manipulation robots' main characteristic, that is, their ability to switch from one production task to another.

23.6.1 Impedance Control

Whitney first reported use of force feedback control of a manipulator for impedance control.[6] Impedance control is a fundamental approach toward allowing a stiff industrial robot to interact with the environment. Impedance control is mainly directed to contact tasks for which the control of interaction force is not essential for successful task execution. These contact tasks, such as insert, require a specific motion of the workpiece that adheres to external constraints in the presence of possible contact with the environment (constrained or compliant robot motion).

These compliant motion tasks require solution of motion control problems. The objective of the impedance control is to reduce contact impedance or stiffness of the position-controlled robot. This is done by controlling dynamic reaction to the external contact forces (robot compliance) to compensate for uncertainties and tolerances in the robot–environment location, while maintaining acceptable force magnitudes. The interaction force between a robot and a fixed environment depends on motion and target impedance. Under certain circumstances, impedance control may also be applied to produce a desired force.

An impedance control task is specified in terms of desired motion trajectory and relationships between position error and interaction force exerted at the end effector. To ensure successful accomplishment of a constrained motion task, the commonly stiff robot position control behavior must be replaced with a compliant *target impedance model.*

The objective of impedance control differs from the conventional control goals in the sense that the main control issue is not to ensure tracking of a reference input signal (e.g., nominal position or force). The aim is to produce a reference target model (*target impedance*) specifying the interaction of robot and environment, i.e., the desired relationship between acting forces and robot motion reaction (position error). A conventional control system is usually analyzed for its ability to track standard input signals (e.g., step, ramp) within the allowed time. The main impedance control performance specification, however, addresses the capability of achieving the target model.

The impedance control problem can be defined as designing a controller so that interaction forces govern the error between desired and actual positions of the end effector. The control input

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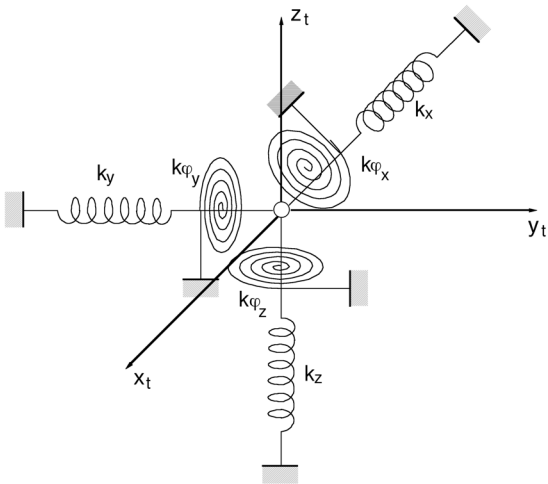

FIGURE 23.7 Target stiffness model in C frame.

describing a desired target impedance relation may, in principle, have an arbitrary functional form, but it is commonly adopted in the linear second order differential equation form describing the simple six-dimensional decoupled mass–spring–damper mechanical system. The reason is that the dynamics of a second order system is well understood. Lee and Lee[46] developed a control algorithm referred to as generalized impedance control by introducing a higher order impedance relation between position and force errors, which includes force derivatives.

In other words, impedance control is a general approach to contact task control in which the robot behaves as a mass–spring–dashpot system whose parameters can be specified arbitrarily. This can be achieved by feedback control using position and force sensing. The following control objective should be obtained:

$$\mathbf{F} = \mathbf{M}_t(\ddot{\mathbf{x}} - \ddot{\mathbf{x}}_0) + \mathbf{B}_t(\dot{\mathbf{x}} - \dot{\mathbf{x}}_0) + \mathbf{K}_t(\mathbf{x} - \mathbf{x}_0) = \mathbf{M}_t\ddot{\mathbf{e}} + \mathbf{B}_t\dot{\mathbf{e}} + \mathbf{K}_t\mathbf{e} \tag{23.14}$$

or in the s domain:

$$\mathbf{F}(s) = \mathbf{Z}_t(s)(\mathbf{x} - \mathbf{x}_0) = \mathbf{Z}_t(s)\mathbf{e} = (\mathbf{M}_t s^2 + \mathbf{B}_t s + \mathbf{K}_t)(\mathbf{x} - \mathbf{x}_0) \tag{23.15}$$

where $\mathbf{Z}_t(s) = \mathbf{M}_t s^2 + \mathbf{B}_t s + \mathbf{K}_t$ is the *target robot impedance* in Cartesian space, $\mathbf{x}_0$ describes the desired position trajectory, $\mathbf{x}$ is the actual position vector, $\mathbf{e}$ is the position control error, $\mathbf{F}$ is the external force exerted upon the robot, and $\mathbf{M}_t$, $\mathbf{B}_t$, and $\mathbf{K}_t$ are positive definite matrices that define target impedance, where $\mathbf{K}_t$ is the stiffness matrix, $\mathbf{B}_t$ is the damping matrix, and $\mathbf{M}_t$ is the inertia matrix. The diagonal elements of these target model matrices describe the desired robot mechanical behavior during contact.

One of the most common approaches for representation of robot and object positions is based on coordinate frames. It is convenient to describe the robot impedance reaction to external forces with respect to a frame, referred to as a *compliance* or *C frame*. Along each C frame direction, the target model describes a mechanical system presented in (Figure 23.7) with the programmable impedance (mechanical parameters); for simplicity, only spring elements are depicted. The model describes a virtual spatial system consisting of mutually independent spatial mass–damper–spring subsystems in six Cartesian directions. A corresponding decoupled physical system is difficult to

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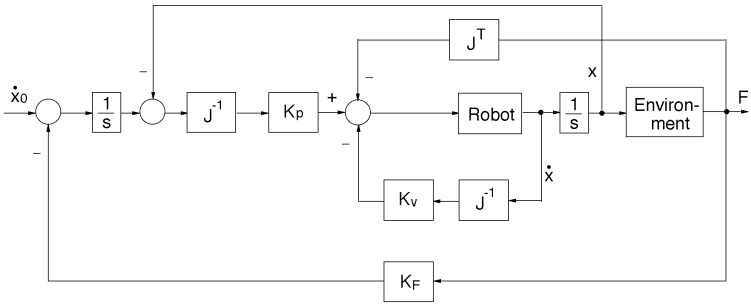

FIGURE 23.8 Damping control.

realize (for example, by combining Cartesian linear axes and Cardan frames). Appropriate selection of target impedance parameters along specific axes is required to achieve active impedance control.

The target impedance matrices can be selected to correspond to various objectives of the given manipulation task.[14] Obviously, high levels of stiffness are required in the directions where the environment is compliant and positioning accuracy is important. Low stiffness can be selected in directions where small interaction forces must be maintained. Large $\mathbf{B}_t$ values are specified when energy must be dissipated, and $\mathbf{M}_t$ is used to provide smooth transient system response during contact.

To assess how well a designed impedance controller meets the above control objective, it is customary to specify performance criteria. A reasonable measure to express the performance of the impedance control is the difference between the target model and real system behavior described by robot motion and interaction forces.[47] Depending on which of these physical values is used to characterize the system behavior (force or position), the *impedance control error* can be expressed by means of *force measure* (*force model error*):

$$\mathbf{e}_f = \mathbf{M}_t(\ddot{\mathbf{x}} - \ddot{\mathbf{x}}_0) + \mathbf{B}_t(\dot{\mathbf{x}} - \dot{\mathbf{x}}_0) + \mathbf{K}_t(\mathbf{x} - \mathbf{x}_0) - \mathbf{F} \tag{23.16}$$

or by *position measure* (*position model error*):

$$\mathbf{e}_p = \mathbf{x} - \mathbf{x}_0 - \delta\mathbf{x}_f \tag{23.17}$$

where the target position deviation is obtained as the solution of the target model differential equation:

$$\mathbf{F} = \mathbf{M}_t\delta\ddot{\mathbf{x}}_f + \mathbf{B}_t\delta\dot{\mathbf{x}}_f + \mathbf{K}_t\delta\mathbf{x}_f \tag{23.18}$$

for the initial conditions: $\mathbf{F}(t_0) = 0;\ \delta\mathbf{x}_f(t_0) = \delta\mathbf{x}_0$.

The computing of the model errors requires both force and the robot position to be measured.

The above defined control goal can be achieved using various control strategies. Impedance control represents a strategy for constrained motion rather than a concrete control scheme. Various control concepts and schemes were established for controlling the relation between robot motion and interaction force.

One of the first approaches to impedance control was proposed by Whitney[18] (Figure 23.8). In this approach known as *damping* or *accommodation control*, the force feedback is closed around the velocity control loop. The interaction force is converted into a velocity modification command by a constant damping coefficient K_F. Using a simplified example of discrete time force control, Whitney defined the condition for system stability during contact as:

$$0 < T\,K_f\,K_e < 1 \tag{23.19}$$

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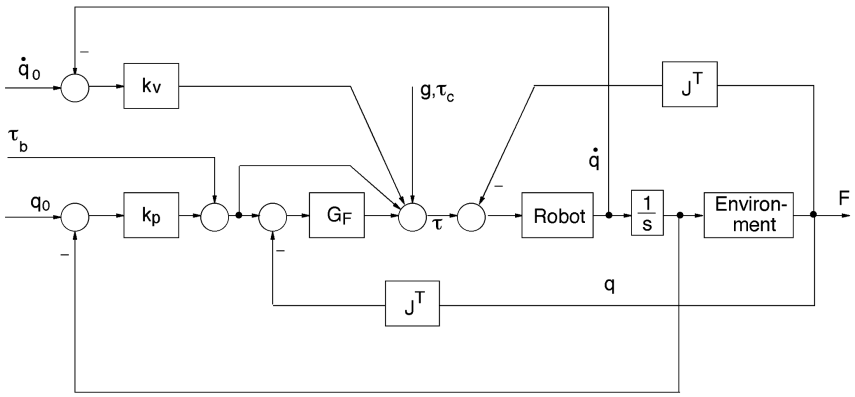

FIGURE 23.9 Stiffness control.

where T is the sampling period, K_f is the force control gain (damping coefficient), and K_e is the stiffness of the environment. This condition implies that if K_e is high, the product TK_f must be small. To avoid large contact forces, a very high sampling rate, i.e., small T is required. Alternatively, for contact with a very stiff object Whitney proposed introduction of a passive compliance in order to achieve the equivalent environmental stiffness K_e smaller (including the stiffness of the robot structure, environment, sensor, etc.).

Salisbury[17] proposed modification of the end effector position in accordance with the interaction force (Figure 23.9). This concept is based on a *generalized stiffness* formulation $\mathbf{F} = \mathbf{K}\,\delta\mathbf{x}$ where $\delta\mathbf{x}$ is a generalized displacement from a nominal commanded end effector position, and $\mathbf{K}$ is a six-dimensional stiffness matrix. Based on the difference between the desired and actual end positions, a nominal force is computed and converted into joint torques using the transpose of the Jacobian matrix. This force is then used to determine the torque error on each joint that is further used to correct applied torque so that the desired force (i.e., stiffness) is maintained at the robot hand. The requirements of the stiffness matrix elements and their designs for specific tasks are considered in Whitney.[6]

These impedance control schemes are simple and relatively easy to implement. However, the achieved closed loop impedance behavior in the Cartesian space depends on robot configuration. Obviously, to replace the nonlinear dynamic model with the linear time-invariant target system (e.g., mass–damper–spring system) generally requires the control law to compensate for relevant system nonlinearities (*model-based dynamic control*).

The most common impedance control concept was established by Hogan[19] who defined a unified theoretical framework for understanding the mechanical interactions between physical systems. This approach focuses on the characterization and control of dynamic interaction based on manipulator behavior modification. In this sense, impedance control is an augmentation of position control. The actions of the manipulator control and hardware and the interaction between a robot and its environment are described by network analysis. The important issue is that the command and control of a vector such as position or force is not enough to control the interaction between systems (dynamic networks). The controller must also be able to command and control a relationship between system variables. The proposed control design strategy is to adapt the robot behavior to become the inverse of the environment. This means that if the environment behaves like admittance, the impedance control should be applied and vice versa.

23.6.1.1 Force-Based Impedance Control

Most of the impedance control algorithms utilize the computed torque method to cancel nonlinearity in robot dynamics in order to achieve linear target impedance behavior. This popular approach requires computation of a complete dynamic model of constrained motion, which make its realization rather

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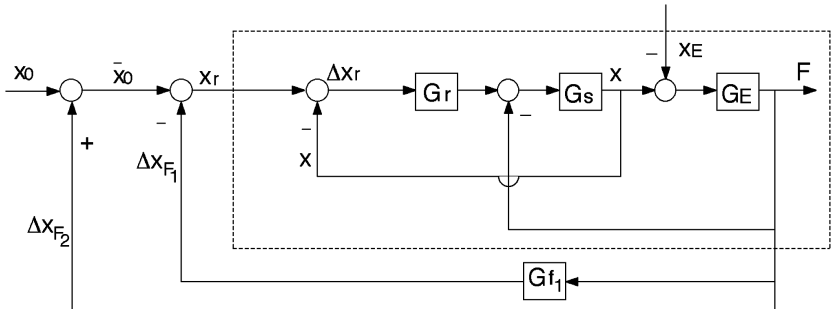

FIGURE 23.10 Force-based dynamic impedance control.

complex. An important drawback of this approach is sensitivity to model uncertainties and parameter variations. Performance improvements that can be achieved with algorithms in industrial robotics are not in proportion to implementation efforts.

Hogan[48] proposed several techniques with and without force feedback for modulating the end point impedance of a general nonlinear manipulator. Assuming the Cartesian dynamic model perfectly matches the real system, Hogan proposed the following nonlinear control law:

$$\boldsymbol{\tau} = \hat{\Lambda}\mathbf{M}_t^{-1}\left[\mathbf{K}_t(\mathbf{x}_0 - \mathbf{x}) - \mathbf{B}_t\dot{\mathbf{x}} + \mathbf{F}\right] + \hat{\boldsymbol{\mu}}(x,\dot{x}) + \hat{\mathbf{p}}(x) - \mathbf{F} \tag{23.20}$$

be applied to reach a reasonable target impedance behavior in the ideal case in the form:

$$\mathbf{F} = \mathbf{M}_t\ddot{\mathbf{x}} + \mathbf{B}_t\dot{\mathbf{x}} + \mathbf{K}_t(\mathbf{x} - \mathbf{x}_0). \tag{23.21}$$

The control scheme corresponding to the above control law is sketched in (Figure 23.10). A distinction is made in the figure between the active force exerted by the robot ($\overline{\mathbf{F}}$) and the reactive external force (F), which can be computed assuming a simple spring-like environmental model:

$$\overline{\mathbf{F}} = \mathbf{K}_e\left(\mathbf{x} - \mathbf{x}_e\right) = -\mathbf{F} \tag{23.22}$$

where $\mathbf{K}_e$ is the stiffness of the environment. This control law essentially represents a nonlinear control algorithm that combines the *inverse control technique*[49] (also known as *computed torque method* and *nonlinear decoupling*) and force-based (inner loop) impedance control. In force-based impedance control algorithms (Figure 23.10), an expected reference force is computed to satisfy the desired impedance specification based on position error and target impedance $\mathbf{F}_0(s) = \mathbf{Z}_t(s)\left(\mathbf{x}_0 - \mathbf{x}\right)$. The expected active force $\mathbf{F}_0$ is compared with the actual force sensed by the force sensor and a force error is computed. This error is further multiplied with inertia matrices $\hat{\Lambda}\mathbf{M}_t^{-1}$. Finally, the product is summed with dynamic compensation terms (Coriolis and gravitation vectors) and feed-forward force $\overline{\mathbf{F}}$ to obtain Cartesian control force, which is further transferred into the robot joint via the transposed Jacobian $\mathbf{J}^T$ to get the actuator torque control inputs. It is relatively easy to prove that the control law:

$$\boldsymbol{\tau} = \hat{\Lambda}\left\{\ddot{\mathbf{x}}_0 + \mathbf{M}_t^{-1}\left[\mathbf{K}_t(\mathbf{x}_0 - \mathbf{x}) + \mathbf{B}_t(\dot{\mathbf{x}}_0 - \dot{\mathbf{x}}) + \mathbf{F}\right]\right\} + \hat{\boldsymbol{\mu}}(x,\dot{x}) + \hat{\mathbf{p}}(x) - \mathbf{F} \tag{23.23}$$

realizes the impedance control behavior specified in Equation (23.15).

The reason impedance control methods based on force control input cannot be suitably applied in commercial robotic system lies in the fact that commercial robots are designed as positioning

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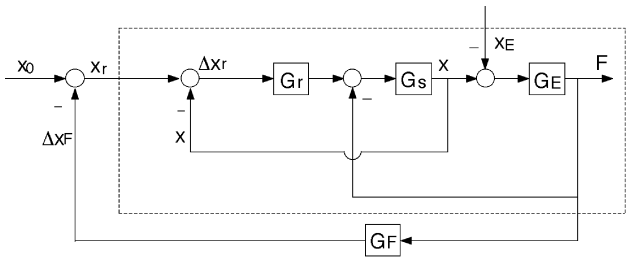

FIGURE 23.11 Position model-error impedance control.

devices. In the above methods, the driving torque vector ensuring the desired target impedance behavior has been computed and then multiplied by the transpose of the Jacobian matrix in order to be realized around the actuated robot joints. However, the realization of computed torque is not accurate in commercial robotic systems because the local servos are position controlled and there is no force feedback with respect to the torques around the joints. Consequently, the realization of desired torques is poor, since high friction and other nonlinearities in the transmission mechanisms contribute significantly to the inaccuracy of current/torque causality. Because of these difficulties, the implementation of force-based impedance control can be successfully performed only by a new generation of direct-drive robots[50] with accurate joint torque controls. Force-based impedance control requires a completely new control system.

23.6.1.2 Position Based Impedance Control

As mentioned above, force-based impedance control is mainly intended for robotic systems with relatively good causality between joint and end effector forces, such as direct-drive manipulators. In commercial robots, the effects of nonlinear friction in transmission systems with high gear ratios significantly destroy this causality. Therefore, in commercial robotic systems, it is feasible to implement only the position-mode impedance control by closing a force-sensing loop around position controller. Position-based impedance control is most reliable and suitable for implementation in industrial robot control systems since no modification of a conventional positional controller is required.

Two basic impedance control schemes with internal position controls can be distinguished.[51] The first scheme is sketched in Figure 23.11. An inner position control loop is closed based on position sensing; it is surrounded by a closed outer loop based on force sensing. The force loop is naturally closed when the end effector encounters the environment. The outer loop includes a force feedback compensator $\mathbf{G}_F$, basically representing admittance since its role is to shape the relation between contact force and corresponding nominal position modifications $\Delta\mathbf{x}_f$. This block is imposed on the system to regulate the force response to the commanded and actual motions according to the target admittance $\mathbf{Z}_t^{-1}$.

Other control blocks in Figure 23.11 represent a common industrial robot position control system involving the following transfer function matrices: $\mathbf{G}_r$, position control regulator; $\mathbf{G}_s$, robot plant; and $\mathbf{G}_e$, environment. The position correction $\Delta\mathbf{x}_F$ is subtracted from the nominal position $\mathbf{x}_0$ and the command input vector for the positional controller, referred to as *reference position* $\mathbf{x}_r$, is computed. A good tracking of the reference position must be achieved by the internal position controller. Assuming $\mathbf{G}_F = \mathbf{Z}_t^{-1}$, the position error input to the position controller $\Delta\mathbf{x}_r$ becomes:

$$\Delta\mathbf{x}_r = \mathbf{x}_r - \mathbf{x} = \mathbf{x}_0 - \Delta\mathbf{x}_F - \mathbf{x} = \mathbf{x}_0 - \mathbf{x} - \mathbf{Z}_t^{-1}\mathbf{F} = \mathbf{e}_p . \tag{23.24}$$

This means that the control system in Figure 23.11 utilizes the position-related impedance model error $\mathbf{e}_p$ (23.17) to achieve target impedance behavior. The impedance model error $\mathbf{e}_p$ is fed forward to the position controller $\mathbf{G}_r$ in order to be nullified within internal position control loop. Since the

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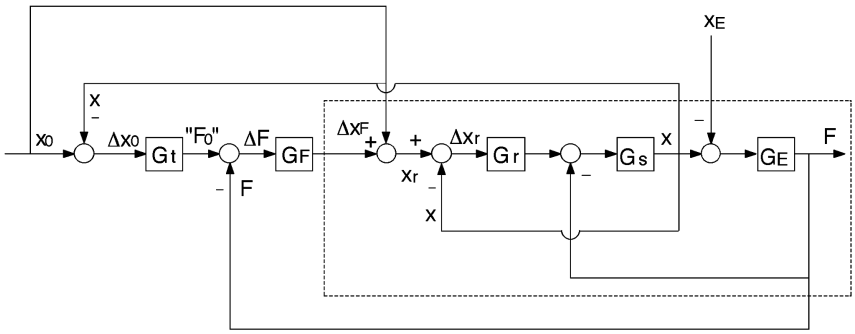

FIGURE 23.12 Force model error-based impedance control.

purpose of the system in (Figure 23.11) is to control position, it will be referred to as *position impedance model error control*.

The second position-based impedance control structure is depicted in (Figure 23.12). This scheme provides a generalization of the original scheme proposed by Maples and Becker[15] and is referred to as *outer/inner loop stiffness control*. The control scheme consists of two parallel feedback loops superimposed to the internal position control and closed using measurements from both the wrist force sensor and position sensors. Analyzing the control scheme, it can be seen that the position error $\mathbf{e} = \Delta\mathbf{x}_0 = \mathbf{x}_0 - \mathbf{x}$ is multiplied by the task-specific target impedance $\mathbf{G}_t(s) = \mathbf{Z}_t(s)$ to provide a *nominal* (reference) *force* $\mathbf{F}_0$, which corresponds to the target impedance behavior on the output. The tracking of this force is realized by the next feedback loop closed on the sensed force $\mathbf{F}$. In the ideal case, we have $\mathbf{F}_0 = \mathbf{F}$, describing the target behavior. Thus Figure 23.12 basically represents a force control system with target impedance added to regulate the motion response to the interaction force. Following the control flow, we see that the force error in this control scheme corresponds to the previously defined force impedance model error (23.17):

$$\Delta\mathbf{F} = \mathbf{F}_0 - \mathbf{F} = \mathbf{G}_t\left(\mathbf{x}_0 - \mathbf{x}\right) - \mathbf{F} = \mathbf{e}_f \tag{23.25}$$

Therefore, we will refer to the control system in Figure 23.12 as *force model error impedance control*. Similarly, to the previous system (Figure 23.11), the model error Equation (23.25) is further relayed to the internal control part in order to regulate this error to zero as time increases. However, different from the position model error control in Figure 23.11, where the position model error is eliminated by the internal position control, in the control system in Figure 23.12, the regulation of the model error is realized by means of the compensator $\mathbf{G}_F$. In order to retain the internal position control loop, the implicit force control structure is implemented by passing the force error $\Delta\mathbf{F}$ through the admittance filter $\mathbf{G}_F$, providing nominal path modification $\Delta\mathbf{x}_F$. The position correction is further added to the Cartesian nominal position $\mathbf{x}_0$, and via reference position $\mathbf{x}_r$ feeds forward to the position servo. Obviously, to achieve $\Delta\mathbf{F} = \mathbf{e}_f \to 0$ as $t \to \infty$ which ensures a steady state position deviation $\left(\mathbf{x}_0 - \mathbf{x}\right)_\infty = \mathbf{e}_\infty$ corresponding to the target impedance (stiffness) model, the regulator $\mathbf{G}_F$ has to involve an integral control term.

This scheme was originally developed as a position-based realization of Salisbury's stiffness control algorithm.[17] In this seminal work,[15] $\mathbf{G}_t$ block was a diagonal stiffness matrix that allowed the user to specify compliance along Cartesian directions, while compensator $\mathbf{G}_F$ was realized as a pure integrator ensuring desired stiffness steady state.

Both control approaches utilize similar concepts to produce the target impedance model by reducing the impedance model errors $\mathbf{e}_p$ and $\mathbf{e}_f$ to zero. Each approach has specific advantages and disadvantages.[51] The $\mathbf{e}_p$-based scheme (Figure 23.11) is simpler and easier to implement. Under some circumstances, this scheme allows different target impedances to be realized by setting the

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compensator $\mathbf{G}_F$ to the target admittance, while the position controller undertakes feedback control. This is similar to an open loop target impedance control. Conversely, in the *force model error control* scheme (Figure 23.12), the target impedance is specified in the outer loop using $\mathbf{G}_t$ block, while the role of the internal loop compensator $\mathbf{G}_F$ is to ensure the tracking of the selected model using force feedback. The internal position control loop is retained to achieve robust position-based, i.e., implicit, force control and control robot motion in the free space. This scheme offers more possibilities to adjust the system contact behavior by choosing $\mathbf{G}_t$ and tuning $\mathbf{G}_F$. However, the opportunity to arbitrarily select the target model and dynamically maintain the force/motion relationship is limited by the complex structure of this scheme.

The main problem with the $\mathbf{e}_f$-based scheme lies in the transition to and from contact (constrained motion). The external impedance loop in this scheme is closed even in the free space when the contact force is zero, and thus affects position control performance. Although the magnitude of the position deviation can be insignificant, considering that the stiffness of the position control is essentially greater than the target one and the inner position loop is faster than the external impedance loops, this effect is not desirable in practice. The compensator $\mathbf{G}_F$ has to be tuned to achieve the required control goal in the presence of a stiff environment, e.g., a large amount of damping to ensure a stable transition. However, that is contrary to the position control performance needed in the free space. In the $\mathbf{e}_p$-based scheme (Figure 23.11), the force feedback loop is closed naturally by physical contact and interaction force sensing. In the free space, only the forward position control is active.

To avoid this shortcoming of the $\mathbf{e}_f$-based impedance control manifested by deviations of position control performance in the free space through impedance control blocks $\mathbf{G}_t$ and $\mathbf{G}_f$ (Figure 23.12), the outer part of the control scheme providing the position modification $\Delta\mathbf{x}_F$ can be deactivated in the free space and activated only on contact with the environment (control switching, variable structure control). The contact state can be observed using force sensor information and a force threshold, which should prevail over noise effects in the force sensing (e.g., offsets, high frequency oscillations, gripper inertial forces during robot motion, etc.). Generally, however, the switching algorithms are not easy to implement. This causes the force model error control scheme to be even more difficult to integrate into today's industrial controllers. Moreover, in conjunction with control delays, the change of control structure can cause undesirable chattering in the contact task, which will lead to contact and system instability. Thus, the design of a stable impedance controller becomes a complex undertaking with this scheme.

The $\mathbf{e}_p$*-based* control scheme (Figure 23.11) was recently implemented in the new SPARCO space control system[52] developed based on industrial robot standards. Its impedance control is completely integrated at several levels including servo control, virtual force sensor (data processing, filtering, calibration), motion planning, language supports, and monitoring functions. The SPARCO control servo scheme involves an improved position-based control law. The impedance control design problem is split into two subproblems: realization of target impedance model, and choice of target impedance parameters to achieve stable interaction with the environment and required performance. The compensator $\mathbf{G}_F$ that produces the target impedance $\mathbf{G}_t$ is obtained from the following relations (Figure 23.11):

$$\begin{aligned} \mathbf{G}_s^{-1}(s)\mathbf{x} &= \mathbf{G}_r(s)\left[\mathbf{x}_r - \mathbf{x}\right] - \mathbf{F} \\ \mathbf{x}_r &= \mathbf{x}_0 - \Delta\mathbf{x}_f \\ \Delta\mathbf{x}_F &= \mathbf{G}_F(s)\mathbf{F} \end{aligned} \tag{23.26}$$

Substituting:

$$\mathbf{x} - \mathbf{x}_0 = \mathbf{G}_t^{-1}(s)\mathbf{F} \tag{23.27}$$

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in (23.26), we derive the expression for the position modification $\Delta \mathbf{x}_f$ which ensures the realization of the target model in the form:

$$\Delta \mathbf{x}_F = \mathbf{G}_p^{-1}(s)\left[\left(\mathbf{G}_t^{-1}(s) - \mathbf{S}_p(s)\mathbf{G}_s(s)\right)\mathbf{F} - \mathbf{S}_p(s)\mathbf{x}_0\right] \tag{23.28}$$

where $\mathbf{S}_p(s)$ is the sensitivity transfer function matrix $\mathbf{S}_p(s) = \mathbf{I} - \mathbf{G}_p(s)$. This control law involves the impedance compensator:

$$\mathbf{G}_F(s) = \mathbf{G}_p^{-1}(s)\left(\mathbf{G}_t^{-1}(s) - \mathbf{S}_p(s)\mathbf{G}_s(s)\right) = \mathbf{G}_p^{-1}(s)\mathbf{G}_t^{-1}(s) - \mathbf{G}_r^{-1}(s) \tag{23.29}$$

and an additional nominal position feed forward term:

$$\mathbf{G}_p^{-1}(s)\mathbf{S}_p(s)\mathbf{x}_0 = \mathbf{G}_r^{-1}(s)\mathbf{G}_s^{-1}(s)\mathbf{x}_0 \tag{23.30}$$

In the linearized robot control system, this control law provides equivalent effect as the computed torque-based impedance control (Equation 23.23). Essentially, the main issue is to compensate for dynamic effects in the forward position control in order to achieve the given target model, which is similar to the nonlinear control (Equation 23.23) goal. The difference is that control law defined in Equation (23.29) is based on linearized compensation techniques, which are less complex than computation of nonlinear robot dynamics. However, the impedance compensator (Equation 23.29) includes the inverse of position controller $\mathbf{G}_r^{-1}(s)$ and the position control closed loop system matrix $\mathbf{G}_p^{-1}(s)$. Generally these matrices depend on robot configuration. Moreover, using the inverse compensators is not well suited in practice, since inverse systems produce large control signals, amplify high frequency noise, and may introduce unstable pole zero cancellations.

However, as demonstrated in Šurdilović,[53] these shortcomings do not appear in industrial robots. The performance of commercial industrial robotic systems allows significant simplification of impedance control design and implementation. The robustness of internal position control allows the disturbances due to interaction force and joint friction effects to be neglected. In other words, the term $\mathbf{G}_r^{-1}(s)$ from Equation 23.29 can be omitted, since the internal position controller (Figure 23.11) significantly reduces the interaction force disturbance effects. Furthermore, due to high gear ratios and accurate design of joint position controllers, the closed loop position control transfer matrix $\mathbf{G}_p(s)$ is *normal*, *diagonally dominant,* and *spatially rounded* with good approximation. In other words, it exhibits similar performance independent of Cartesian directions, and compliance frame selection achieves similar performance in a large workspace area (Figure 23.4).

Necessary conditions to ensure the *spatial roundness* and *diagonal dominance* of convenient position control systems of industrial robots are derived in Šurdilović.[53] In the majority of industrial robot systems, diagonal dominance is achieved by high transmission ratios in joints, causing constant rotor inertia to prevail over variable inertia of the robot arm. The spatial roundness in the joint and Cartesian space is achieved by uniform tuning of local axis position controllers. This characteristic is illustrated in Figure 23.4 by the spherical form of the principal gain space of the closed loop position control transfer matrix $\mathbf{G}_p(s)$. These characteristics are important in decentralized position control in order to ensure robust and uniform performance in Cartesian space. They allow impedance control to be implemented simply, using the constant compensator $\mathbf{G}_F$.

In spite of implementation of inverse compensators, we can require that $\mathbf{G}_p^{-1}(s)$ show inverse characteristics only over some finite frequency range. To obtain a proper compensator, we can employ a low pass filter (by inserting more poles), or utilize the low pass performance of the target admittance $\mathbf{G}_t^{-1}(s)$. Moreover, assuming that the nominal motion exhibits slow acceleration/deceleration in the vicinity of constraints and during contact, which is a reliable premise due to unknown

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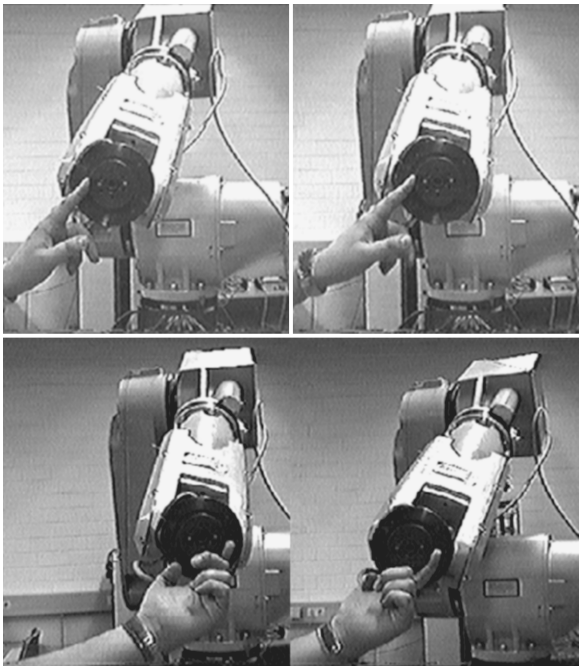

FIGURE 23.13 Target model realization experiment.

constraints, we can also neglect the feed forward term (Equation 23.30) and thus substantially simplify the control law:

$$\mathbf{G}_F(s) = \hat{\mathbf{G}}_p^{-1}(s)\mathbf{G}_t^{-1}(s) \tag{23.31}$$

where $\mathbf{G}_t$ is the diagonal target end effector impedance matrix specifying the target behavior in each compliance frame direction corresponding to Equation (23.14) and $\hat{\mathbf{G}}_p$ is the diagonal estimate of the closed loop position transfer matrix, i.e., the estimation of its dominant diagonal part. The controller (Equation 23.31) practically consists of a diagonal and, for a given task, constant compensator. The above control law provides the following nominal closed loop contact behavior:

$$\mathbf{x} = \mathbf{G}_p(s)\mathbf{x}_0 - \mathbf{G}_t^{-1}(s)\mathbf{F} \tag{23.32}$$

In other words, the controller (Equation 23.31) accurately realizes the desired target model in the industrial robot control system. It is obvious that the role of this controller is to shape the sensitivity transfer functions, i.e., the relationship between external interaction force disturbance and the position tracking error according to the desired target impedance model (Equation 23.14), without influencing the nominal position control performance in the free space. Only the sensitivity transfer function to the interaction force sensed by the force sensor and used in the external control loop is modified by the impedance control. The impedance controller does not influence the robust and good perturbation rejection properties of the position controller toward other disturbance effects, such as friction.

A typical result of a target model realization experiment (Figure 23.13) by the control law (Equation 23.31) with the industrial Manutec r3 robot is presented in Figure 23.14. Obviously, a very good match of model and experimental contact forces was achieved. The bandwidth of the position-based impedance controller is theoretically limited by the bandwidth of the internal position

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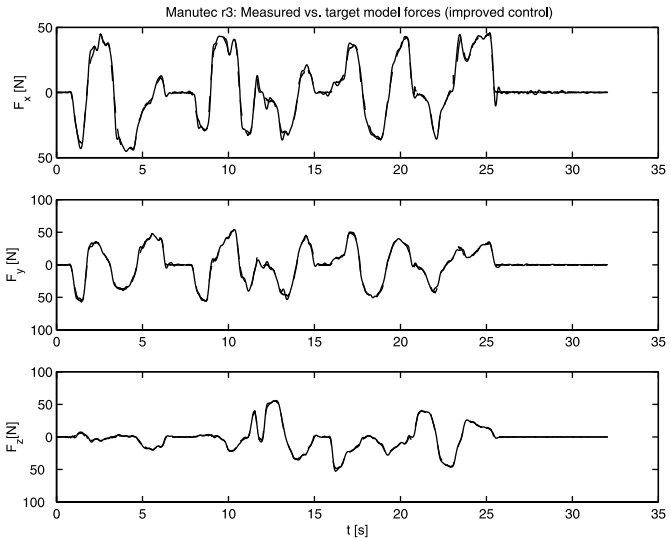

FIGURE 23.14 Target model (solid) and measured (dashed) forces (improved law).

controller (commonly about 10 Hz). However, in practice, impedance controller bandwidth up to 5 Hz is reliable.

The main advantage of the *position model error* scheme over the *force model* scheme, lies in its reliability and simpler design and implementation. The achieved system behavior is easy to understand. Furthermore, taking into account the reliable performance of the industrial robot position control, a sufficiently accurate and robust desired impedance behavior can be achieved with this scheme.

The position-based impedance approach in general suffers from its inability to provide soft impedance due to limits in the accuracy of the position control system and sensor resolution. This approach is mainly suitable for applications that require high position accuracy in some Cartesian directions, which is accomplished by stiff and robust joint control. Design and implementation of this scheme is simple and does not require complex computations.

The force (i.e., torque)-based approach is better suited to providing small impedance (stiffness and damping) while reducing the contact force. From a computational viewpoint, this approach is reasonable for applications where manipulator gravity is small and slow motion is required. In other cases, manipulator modeling details (i.e., complete dynamic models) are needed. Contrary to the position-based impedance control, the force-based control is mainly intended for robotic systems with relatively good causality between joint torques and end effector forces, such as direct drive manipulators.

23.6.1.3 Other Impedance Control Approaches

Considerable research efforts addressed the development of *adaptive impedance control algorithms*. Daneshmend et al.[27] proposed a model reference adaptive control scheme with Whitney's damping control loop. Several authors have pursued Craig's adaptive inverse dynamic control algorithms[54] and expanded its application to contact motion. Lu and Goldenberg[47] proposed a sliding mode-based control law for impedance control. The proposed controller consists of two parts: a nominal dynamic model to compensate for nonlinearities in robot dynamics, and a compensator ensuring the impedance error (i.e., the difference between nominal target model and the actual impedance) proceeds asymptotically to zero on the sliding surface. In order to cope with the chattering effects in the variable structure sliding mode control, a continuous switching algorithm in a small region around sliding surface is proposed. Al-Jarah and Zheng[55] proposed an interesting adaptive impedance control algorithm intended to minimize the interaction force between manipulator and environment.

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Dawson et al.[30] developed a robust position/force control algorithm based on the impedance approach. The control scheme consists of two blocks: a desired trajectory generator computing the modified command position based on the target impedance model and using the nominal position and force measurements, and a controller involving a PD regulator and robust control part. The purpose of the robust controller is to ensure that the control tracking error (i.e., the difference between target and actual robot impedance) proceeds asymptotically to zero in spite of model uncertainties within specified bounds. Robust control design is currently one of the most challenging topics in controlling contact tasks.

Under some circumstances, the impedance control can be applied to achieve desired contact forces. When an impedance-controlled manipulator is in contact with the environment, the interaction force is completely determined by the input position, target impedance, and the model (impedance) of the environment. It is then apparent from Equations (23.14-15) that the interaction forces can be precisely controlled using the impedance approach as long as an exact model of the environment and the robot is available. By using the force-based approach in this case, the desired force can be achieved in the open loop, and a force sensor is not needed. Such an approach is very similar to the passive gain adjustment.

In general, however, it is difficult to exactly know the location and impedance of the environment and robotic system. If the stiffness of the environment is much greater than the stiffness of the target impedance and the robot, the force can also be controlled in a desired accuracy range by using only the impedance model, rather than only knowledge about the environment.[51] When these conditions are not fulfilled, i.e., stiffness of the environment is not much greater than that of the target impedance, it is necessary to perform estimation experiments to obtain the model of the environment and control the contact force. However, the on-line estimation of the environment is complex and coupled with several practical problems: uncertain robot motion sensing at low velocities, noise, disturbances due to friction and vibrations, impact, etc., that can significantly influence the results. Using the robot to acquire the data for an off-line estimation is risky in principle, and in tasks with variable environment, virtually impossible.

23.6.2 Hybrid Position/Force Control

This approach is based on a theory of compliant force and position control formalized by Mason[1] and concerns a large class of tasks involving partially constrained motion of the robot. Depending on the specific mechanical and geometrical characteristics of the contact problem, this approach makes a distinction between two sets of constraints upon robot motion and contact forces. The constraints that are natural consequences of the task configuration, i.e., of the nature of the desired contact between an end effector held by the robot and a constrained surface, are called *natural constraints*. Physical objects impose natural constraints. As already mentioned, a suitable frame in which the task to be performed is easily described, i.e., in which *constraints* are specified, is referred to as the *constraint frame* (or *task frame* or *compliance frame*).[56] For example, for a surface sliding contact task, it is customary to adopt the Cartesian constraint frame as sketched in Figure 23.15. Assuming an ideal rigid and frictionless contact between the end effector and the constraint surface, it is obvious that natural constraints restrict end effector motion in z direction and rotations about x and y axes. The frictionless contact prevents the forces in these directions and allows the torque around the z axis to be applied.

In order to specify the task of the robot with respect to the compliant frame, *artificial constraints* must be introduced. The artificial constraints must be imposed by the control system. These constraints essentially partition the possible DOFs of motion in those that must be position controlled and those that should be force controlled in order to perform the given task. The need to define an artificial constraint with respect to force when there is a natural constraint on the end-effector motion in this direction (i.e., DOF) and vice versa (Figure 23.15) is obvious.

To implement hybrid position/force control, a diagonal Boolean matrix $\mathbf{S}$, called the *compliance selection matrix*,[7] has been introduced in the feedback loops to filter out sensed end effector forces

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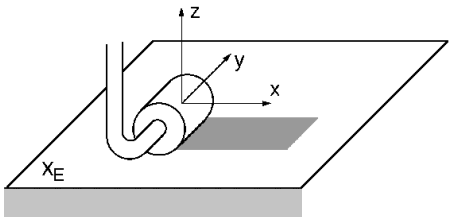

Natural Constraints		Artificial Constraints	
	$F_x = 0$		$v_x = V$
	$F_y = 0$		$v_y = 0$
$v_z = 0$		$F_z = 0$	
$\omega_x = 0$		$M_x = 0$	
$\omega_y = 0$		$M_y = 0$	
	$M_z = 0$		$\omega_z = 0$

FIGURE 23.15 Specification of surface sliding hybrid position/force control task.

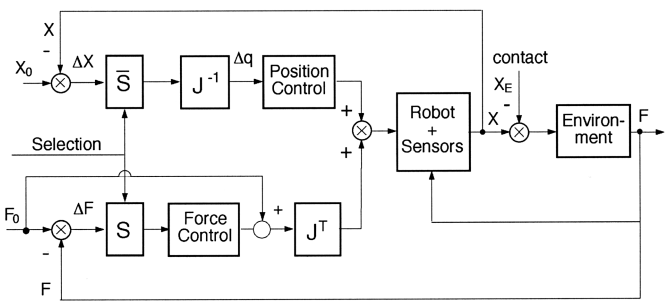

FIGURE 23.16 Explicit hybrid position/force control.

and displacements that are inconsistent with the contact task model. In accordance with the specified artificial constraints, the *i*-th diagonal element of this matrix has the value 1 if the *i*-th DOF with respect the task frame is to be force controlled and the value 0 if it is position controlled. To specify a hybrid contact task, according to Mason,[1] the following information sets must be defined:

1. Position and orientation of the task frame
2. Denotation of position and force controlled directions with respect to the task frame (selection matrix)
3. Desired position and force setpoints expressed in the task frame

Once the contact task is specified, the next step is to select the appropriate control algorithms. The relevant methods are discussed below.

23.6.2.1 Explicit Force Control

The most important method within this group is certainly the algorithm proposed by Raibert and Craig.[7] Figure 23.16 represents the control scheme that illustrates the main idea. The control consists of two parallel feedback loops, the upper one for the position, and the lower one for the force

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feedback loop. Each of these loops uses separate sensor systems. The positional loop utilizes the information obtained from the positional sensors at the robot joints, and the force loop is based on force-sensing data. Separate control laws are adopted for each loop. The central idea of this hybrid control method is to apply two outwardly independent control loops assigned to each DOF in the task frame. Both control loops cooperate simultaneously to control each of the manipulator joints. This concept, at first glance, appears to be ideal for solving hybrid position/force control problems. However, a deeper insight into the method reveals some essential difficulties and problems.

The first problem is related to the opposite requirements of the hybrid control concept concerning position and force control subtasks. Namely, the position control must be very stiff to keep the positioning errors in the selected directions as small as possible. The force control requires a relatively low stiffness of the robot (corresponding to the desired force) in the force controlled direction with respect to the task frame to ensure that the end effector behaves compliantly with the environment. As explained above, the explicit hybrid control attempts to solve this problem by control decoupling into two independent parts that are position and force controlled (Figure 23.16). In the force-controlled directions, the position errors decrease to zero by multiplication with the selection matrix orthogonal complement (position selection matrix) defined as $\bar{\mathbf{S}} = \mathbf{I} - \mathbf{S}$.* This implies that the position control part does not interfere with the force control loop, but that is not the case. The joint space nature of robot control realization results in a coupling between position and force control loops that are previously decoupled mathematically in the task frame. Assuming a proportional plus differential (PD) position control law, and assuming that the force control consists of a proportional plus integral controller (PI) with gain $\mathbf{K}_{Fp}$ and $\mathbf{K}_{Fi}$, respectively, and a force feed forward part, the control law according to the scheme in Figure 23.16 can be written in the Cartesian space as:

$$\boldsymbol{\tau} = \mathbf{K}_p\, \bar{\mathbf{S}}\, \Delta\mathbf{x} + \mathbf{K}_v\, \bar{\mathbf{S}}\, \Delta\dot{\mathbf{x}} + \mathbf{K}_{Fp}\mathbf{S}\Delta\mathbf{F} + \mathbf{K}_{Fi}\mathbf{S}\int \Delta\mathbf{F}dt + \mathbf{F}_0 \tag{23.33}$$

Based on relationships between Cartesian and joint space gains, Zhang and Paul[26] proposed an equivalent hybrid control law in the joint space:

$$\boldsymbol{\tau}_\mathbf{q} = \mathbf{J}^T\boldsymbol{\tau} = \mathbf{k}_p\mathbf{J}^{-1}\bar{\mathbf{S}}\,\mathbf{J}\,\Delta\mathbf{q} + \mathbf{k}_v\,\mathbf{J}^{-1}\,\bar{\mathbf{S}}\,\mathbf{J}\,\Delta\dot{\mathbf{q}} + \mathbf{J}^T(\mathbf{K}_{fp}\mathbf{S}\Delta\mathbf{F} + \mathbf{K}_{fi}\mathbf{S}\int \Delta\mathbf{F}dt + \mathbf{F}_0) \tag{23.34}$$

Since each robot joint contributes to the control of both position and force, couplings in the manipulator's mechanical structure (implied in the Jacobian matrix) cause a control input to the actuator, corresponding to the force loop (e.g., force-controlled directions) to produce additional forces in position-controlled directions in the task frame, and vice versa. It is obvious from Equation (23.33) that by setting the position errors in the force controlled directions to zero (i.e., by filtering the position error through $\bar{\mathbf{S}}$), the position feedback gains in all directions are changed in comparison with the position control in free space. This causes the entire system to become more sensitive to perturbations. As a consequence, the performance of a robot with this scheme is not applicable for all robot configurations or all position/force-commanded directions. Moreover, one can find certain configurations with which, depending on selected force and position directions, the robot becomes unstable with the control law (Equation 23.33). This can be easily demonstrated on a simplified linearized robot model, derived from Equation (23.6) by neglecting the nonlinear Coriolis and centrifugal effects (due to small velocities in the contact task) and assuming that gravitational effects are ideally compensated for:

*For the sake of simplicity it is assumed that the task frame coincides with the Cartesian frame. Generally the selection matrix $\mathbf{S}$ is not diagonal in Cartesian space.[35]

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$$\mathbf{\Lambda}(x)\ddot{\mathbf{x}} = \boldsymbol{\tau} + \mathbf{F}. \tag{23.35}$$

Let us analyze the case where the manipulator is in free space and a noncontacting environment (e.g., in the transition phase when the force-controlled robot is approaching a contact surface after being switched from the position-control mode). Assume that some directions (e.g., orthogonal to the contact surface) have been selected for force control and remaining directions for position control. Taking into account that the force is zero, substituting Equation (23.33) in Equation (23.35) yields:

$$\mathbf{\Lambda}(x)\ddot{\mathbf{x}} + \mathbf{K}_v\bar{\mathbf{S}}\dot{\mathbf{x}} + \mathbf{K}_p\bar{\mathbf{S}}\mathbf{x} = \mathbf{K}_v\bar{\mathbf{S}}\dot{\mathbf{x}}_0 + \mathbf{K}_p\bar{\mathbf{S}}\mathbf{x}_0 \tag{23.36}$$

with a robot closed loop system matrix:

$$\mathbf{A} = \begin{bmatrix} \mathbf{0} & \mathbf{I} \\ \Lambda^{-1}\mathbf{K}_p\bar{\mathbf{S}} & \Lambda^{-1}\mathbf{K}_v\bar{\mathbf{S}} \end{bmatrix}. \tag{23.37}$$

To analyze the stability of this system, we determine the eigenvalues of **A**. As shown in Stokić and Šurdilović,[57] the closed-loop matrix becomes unstable in a number of configurations. Even if we introduce feedback loops with respect to the integrals of position errors in directions that are position controlled, it is always possible to find unstable configurations. These unstable configurations build working subspaces far away from singular positions where the system matrix **A** is intrinsically unstable due to the degeneration of the Jacobian matrix. Moreover, only alterations of the selection matrix can cause switching of robot behavior from stable to unstable and vice versa. The kinematic instability was experimentally tested and proven using the industrial robot control systems.[57]

Although the above stability analysis was based on a linearized model and therefore has some limitations, it provides a simple explanation of the nature of stability problems in hybrid position/force control. Since only the robot's position and the selection matrix influence the instability, this phenomenon is referred to as *kinematic instability.*[58] This phenomenon does not depend on whether the robot is in contact with the constraint surface. However, in contact situations, analysis of this problem is complicated by force/position relationship and the tests become very dangerous. It may be concluded that the kinematic instability problem encountered in the considered explicit hybrid position/force control represents a serious deficiency of this method and significantly reduces its applicability.

In order to overcome the difficulties related to kinematic instability, Zhang[59] proposed to introduce an additional selection of input forces. In other words, the input torques from position and force control parts (Figure 23.16) are decoupled in the task frame before they are applied to the joints. When the robot is in free space, the joint torque from the position control part (Equation 23.34) is initially transferred in the Cartesian-compliant frame, then multiplied with the selection matrix, and again transferred back using the static force transformation (i.e., Jacobian matrix) that provides the following control law for the position loop:

$$\boldsymbol{\tau}_q^{\,p} = \mathbf{J}^T\bar{\mathbf{S}}\mathbf{J}^{-T}\mathbf{k}_p\mathbf{J}^{-1}\bar{\mathbf{S}}\mathbf{J}\Delta\mathbf{q} + \mathbf{J}^T\bar{\mathbf{S}}\mathbf{J}^{-T}\mathbf{k}_v\,\mathrm{J}^{-1}\,\bar{\mathbf{S}}\mathbf{J}\Delta\dot{\mathbf{q}}. \tag{23.38}$$

It is relatively easy to prove that the linearized model (Equation 23.36) becomes kinematically stable with this control law. However, similar to the original control scheme, the eigenvalues of the system change with variation of the robot configuration and with the given task, i.e., selection matrix. This causes the robot performance to be strongly dependent on the configuration and selection of controlled directions.

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Fisher and Mujtaba[60] have shown that kinematic instability is not inherent to the explicit hybrid position/force control scheme; it is a result of an inappropriate mathematic formulation of position/force decomposition via selection matrix **S**. It was demonstrated that in the original hybrid control formulation (Equations 23.33 and 34), the position control loop is responsible for inducing the instability, namely the term $\mathbf{J}^{-1}\,\bar{\mathbf{S}}\,\mathbf{J}$ in Equation (23.34). The crucial error in the position control loop is, in the authors' opinion, made by the decomposition of the robot coordinate (DOF) to position- and force-controlled. Instead, to compute the selected position-controlled DOF and the corresponding selected joint errors, respectively, based on:

$$\mathbf{x}^p = \bar{\mathbf{S}}\mathbf{x} \tag{23.39}$$

and

$$\Delta\mathbf{q}^p = \mathbf{J}^{-1}\Delta\mathbf{x}^p = \mathbf{J}^{-1}\bar{\mathbf{S}}\Delta\mathbf{x} = \mathbf{J}^{-1}\bar{\mathbf{S}}\mathbf{J}\,\Delta\mathbf{q}. \tag{23.40}$$

the authors proposed to use the "correct" relationship between the selected Cartesian errors and the joint errors:

$$\Delta\mathbf{x}^p = \left(\bar{\mathbf{S}}\mathbf{J}\right)\Delta\mathbf{q} \tag{23.41}$$

Taking into account the selection matrix structure, it is obvious that $\left(\bar{\mathbf{S}}\mathbf{J}\right)$ is a singular matrix (with zero rows corresponding to the force DOF). Hence, the selected joint errors equivalent to the selected Cartesian position error are obtained as the minimal 2-norm solution:

$$\Delta\mathbf{q}^p = \left(\bar{\mathbf{S}}\mathbf{J}\right)^+\Delta\mathbf{x}^p = \left(\bar{\mathbf{S}}\mathbf{J}\right)^+\bar{\mathbf{S}}\Delta\mathbf{x} = \left(\bar{\mathbf{S}}\mathbf{J}\right)^+\Delta\mathbf{x} = \left(\bar{\mathbf{S}}\mathbf{J}\right)^+\mathbf{J}\,\Delta\mathbf{q} \tag{23.42}$$

or, when the robot is a singular position type, or has a redundant number of joints, with an additional term from the null space of the Jacobian **J**:

$$\Delta\mathbf{q}^p = \left(\bar{\mathbf{S}}\mathbf{J}\right)^+\Delta\mathbf{x} + \left[\mathbf{I} - \mathbf{J}^+\mathbf{J}\right]\mathbf{z}_q \tag{23.43}$$

where $\mathbf{z}_q$ is an arbitrary vector in the joint space and the plus sign denotes the Moor–Penrose pseudoinverse matrix. Thus, for the case in Equation (23.42), the control law of the position hybrid control part becomes:

$$\boldsymbol{\tau}_q{}^p = \mathbf{k}_p\left(\bar{\mathbf{S}}\,\mathbf{J}\right)^+\mathbf{J}\,\Delta\mathbf{q} + \mathbf{k}_v\left(\bar{\mathbf{S}}\,\mathbf{J}\right)^+\mathbf{J}\,\Delta\dot{\mathbf{q}}. \tag{23.44}$$

To determine how the above kinematic transformations can induce instability of the hybrid control, the authors defined a sufficient condition for kinematic stability. From the control viewpoint, this criterion prevents the second order system gain matrices (Equation 23.33) from becoming negative definite, which is a condition that produces system instability.[59] By testing the kinematic stability conditions for both original and correct selection and position error transformation solutions, the authors have proven that the instability can occur in the first case. The new hybrid control scheme, however, always satisfies the kinematic stability condition — it is always possible to find a vector $\mathbf{z}_q$ to ensure kinematic stability.

The second problem relates to *dynamic stability* issues in force control.[61] These effects concern high gain effect of force sensor feedback (caused by high environment stiffness), unmodeled high

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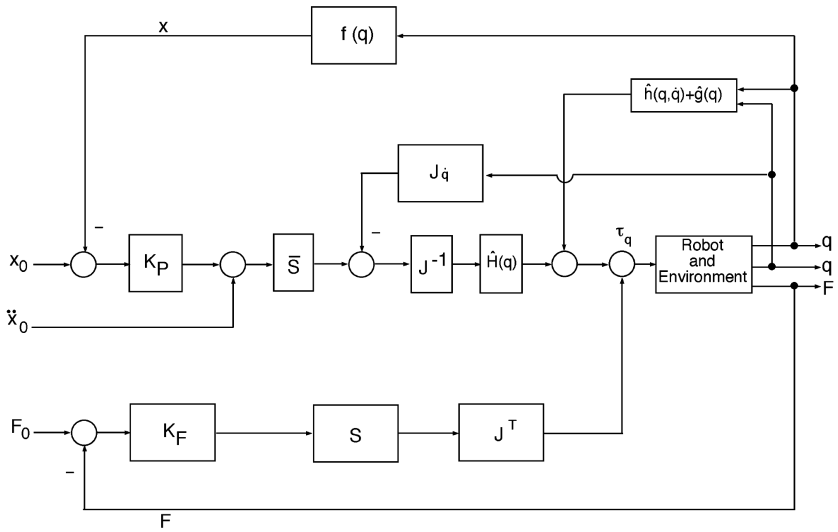

FIGURE 23.17 Resolved acceleration–motion force control.

frequency dynamic effects (due to arm and sensor elasticity), contact with a stiff environment, noncollocated sensing and control, and other factors.

To overcome dynamic problems of hybrid position/force control, several researchers pursued the idea to include the robot dynamic model in the control law. The resolved acceleration control originally formulated for the position control[62] belongs to the group of dynamic position control algorithms. Shin and Lee[31] extended this approach to the hybrid position/force control. The joint space implementation of the proposed control scheme is shown in Figure 23.17. The driving torque compensates for the gravitational, centrifugal, and Coriolis effects, and feedback gains are adjusted according to the changes in the inertial matrix. An acceleration feed-forward term is also included to compensate for changes of nominal motion in position directions. Finally, the control inputs are computed by:

$$\boldsymbol{\tau} = \hat{\Lambda}\ddot{\mathbf{x}}^* + \hat{\boldsymbol{\mu}}(x,\dot{x}) + \hat{\mathbf{p}}(x) + \mathbf{S}\mathbf{f}^* \tag{23.45}$$

where $\ddot{\mathbf{x}}^*$ is the commanded equivalent acceleration:

$$\ddot{\mathbf{x}}^* = \ddot{\mathbf{x}}_0 + \mathbf{K}_v\left(\dot{\mathbf{x}}_0 - \dot{\mathbf{x}}\right) + \mathbf{K}_p\left(\mathbf{x}_0 - \mathbf{x}\right) \tag{23.46}$$

and $\mathbf{f}^*$ is the command vector from the force control parts whose form depends on the applied control law. To minimize the force error, it is convenient to introduce the PI force regulator of the form:

$$\mathbf{f}^* = \mathbf{K}_{fp}\left(\mathbf{F}_0 - \mathbf{F}\right) + \mathbf{K}_{fi}\int\left(\mathbf{F}_0 - \mathbf{F}\right)dt\,. \tag{23.47}$$

Khatib[22] introduced an active damping term into the force control part to avoid bouncing and minimize force overshoots during transition (impact effects):

$$\boldsymbol{\tau}_f = \mathbf{S}\mathbf{f}^* - \hat{\boldsymbol{\Lambda}}\mathbf{S}\mathbf{K}_{vf}\dot{\mathbf{x}} \tag{23.48}$$

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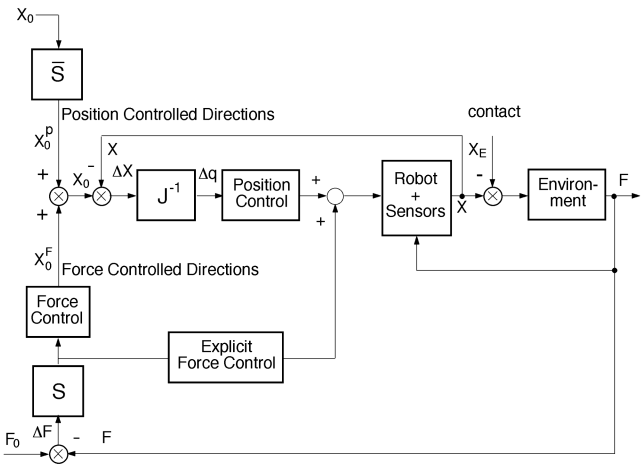

FIGURE 23.18 Implicit hybrid position/force control.

where $\mathbf{K}_{vf}$ is a diagonal Cartesian damping matrix. Bona and Indri[63] proposed further modifications of the control scheme. To compensate for the coupling between force and position control loops and for the disturbance of the position controller due to reaction force, the authors modified the position control law according to:

$$\boldsymbol{\tau}_p = \hat{\Lambda}\bar{\mathbf{S}}\left[\ddot{\mathbf{x}}^* - \hat{\Lambda}^{-1}\left(\mathbf{S}\mathbf{f}^* - \mathbf{F}\right)\right] + \hat{\boldsymbol{\mu}}(x,\dot{x}) + \hat{\mathbf{p}}(x) \tag{23.49}$$

If the dynamic modeling used for computation of the control law is exact, the above control law provides complete decoupling between position and force control in the task frame, i.e., the following closed loop behavior:

$$\ddot{\mathbf{x}} = \bar{\mathbf{S}}\ddot{\mathbf{x}}^* + \mathbf{S}\hat{\boldsymbol{\Lambda}}^{-1}\mathbf{S}\mathbf{f}^* - \mathbf{S}\hat{\boldsymbol{\Lambda}}^{-1}\mathbf{F} - \mathbf{S}\mathbf{K}_{vf}\dot{\mathbf{x}}. \tag{23.50}$$

An experimental evaluation and comparison of explicit force control strategies was presented in Volpe and Khosla.[64]

23.6.2.2 Position Based (Implicit) Force Control

The reason explicit force control methods cannot be suitably applied in commercial robotic systems lies in the fact that commercial robots are designed as positioning devices. The feedback term, i.e., the signal proportional to the force errors, is multiplied by the transposition of the Jacobian matrix in order to calculate the driving torques that have to be realized around the joints to achieve the desired force action (Figure 23.16). These signals are directly fed to the inputs of the local servo parts. However, the computed torques may not be accurate for commercial robotic systems. Since there is no position feedback loop in the force-controlled direction, the robot will move due to various disturbances acting upon it, such as controller and sensor drifts, etc.[57] The implementation of explicit force control can be successfully performed only by a new generation of direct drive robots.

In commercial applied robotic systems, implementing *implicit* or *position-based* force control by closing a force-sensing loop around the position controller (Figure 23.18) appears promising. The input to the force controller is the difference between desired and actual contact force in the task frame. The output is an equivalent position in force-controlled directions which is used as reference input to the positional controller. According to the hybrid force/position control concept,

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the equivalent position in force direction $\mathbf{x}_0^F$ is superimposed to the orthogonal vector $\mathbf{x}_0^P$ in the compliance frame, which defines the nominal position in orthogonal position-controlled directions. The robot behavior in force direction is affected only by the acting force. The positional controller remains unchanged, except for the additional transformations between Cartesian and task frame which have to be introduced since these two frames are not coincident. Since a positional controller provides a basis for realization of force control, this concept is referred to as *implicit* or *position-based* force control,[15] or *external force* control.[13]

The role of force control block in this scheme is two-fold, first, to compensate for the effects of environment (contact process), and second, to achieve tracking of the desired force. Another important quality of a force-controlled manipulator is the ability to respond to positional variations of the contact surfaces. Commonly, a PI force controller has been applied. A more complex force controller including the compensation of the internal position control effects has been proposed in Stokić and Šurdilović.[65] In Figure 23.18 an explicit force control block is added. This scheme combines the implicit and explicit control with the aim of using benefits (robustness and reliability of *implicit* force control and fast reaction of the *explicit* one) and compensating specific disadvantages of single force control approaches.

The main features of the implicit force control scheme are its reliability and robustness. Implemented in commercial robotic systems, this scheme is neither configuration dependent nor sensitive to parameter variation. This control algorithm can be used for arbitrary processes. However, this scheme also exhibits some drawbacks. The accuracy of contact forces is mainly limited by the precision of robot positioning (sensor resolution). The precision can be disturbed when contact with a very stiff environment is requested. Fortunately, inherent compliance of the robot structure or force sensor is always present and reduces the equivalent system stiffness. The performance of implicit force control is significantly limited by the bandwidth of the position controller. A slightly higher bandwidth can be achieved by using a compensator of a higher order. However, due to coupling between position and force-controlled degrees of freedom, whether force control can become significantly faster is questionable.

23.6.2.3 Other Force Control Approaches

The next group of algorithms considers more complex constraints on robot motion. They are described as a set of rigid hypersurfaces in the spaces of end effector Cartesian coordinates,[11] or in the joint coordinate space.[32] The system model is described by a typical set of linearly implicit second order differential algebraic equations (mechanical differential algebraic equations). This model is used to compute the control law to linearize and decouple the system dynamics and divide the control problem into position- and force-controlled directions.

To improve reliability, the dynamic hybrid control is extended to unknown environments that consist of hypersurfaces.[66] The improved control schemes involve on-line identification algorithms based on force and position measurements and adaptive control mechanisms. However, the adaptive constrained motion control is theoretically attractive, but impractical in reality. Hence, the hybrid control algorithms become even more complex and difficult to implement in real time with the computational and sensing resources available for robotic manipulators today.

The hybrid position/force task specification has been a subject of several investigations. Lipkin and Duffy[24] demonstrated that Mason's position/force decomposition approach based on *geometrical orthogonality* is in fact erroneous. The resulting planning for hybrid control is not invariant with respect to translation of origin or change of unit length. The authors proposed a more general and mathematically consistent invariant hybrid task formulation based on screw algebra. The complementarity between motion (modeled by a twist) and force (represented by a wrench) is expressed via a *reciprocity relationship* independent of coordinate frame, scaling, or units. Two fundamental relations between twist and wrench, referred to as *freedom* and *constraint equations*, have been introduced to test task compatibility with the model of the environment. These relations correspond to analytical expressions for natural and artificial constraints in the noninvariant hybrid approach. For every constrained motion

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task, two screw subspaces that correspond to artificial constraints can be derived. These subspaces represent the sets of screws about which twists and wrenches can be controlled.

In certain simple tasks and reference frames, both conventional and reciprocity-based decomposition show the same results. However, the reciprocity-based approach provides a more general decomposition applicable when the freedom and constraint subspaces do not span a six-dimensional space or have nonzero intersections and also to manipulators that have fewer than six DOF.[67]

If the twist and wrench are consistent with the environment (i.e., the freedom and constraint equations are satisfied) the specified task is feasible for hybrid control. In the opposite case, the specified twist and wrench must be filtered to obtain a kinestatically realizable control action (so-called kinestatic filtering).

A procedure to apply the reciprocity-based task decomposition to manipulator dynamics to obtain equations of motion relevant for hybrid control was presented by Sinha and Goldenberg.[68] Several model-based tools for task specification using this approach were presented by Khatib.[22] The reciprocity concept is well suited for nominal specification of arbitrary motion constraints and also serves to define possible uncertainties and on-line identification and observation of real motion constraints. This strategy generally makes task execution against uncertainties very robust. This is particularly essential for contour-following tasks. An overall hybrid position force control scheme based on general decomposition formalism including identification of geometrical uncertainties was proposed by De Schutter and Bruyninckx.[25] Design of appropriate controllers is subject to further researches.

23.6.3 Force/Impedance Control

Several attempts have been made to combine impedance and force control with the aim of compensating for specific disadvantages of single control approaches. Although it is possible under some circumstances to demonstrate correspondence between force and impedance control laws,[69] there are essential differences between these main constraint motion control concepts.

The main advantage of impedance control over force control is easier task specification and programming. A contact task is specified in terms of motion sequences, so the impedance control does not require modifications of conventional free space planning control concepts and algorithms (the programmer can take advantage of existing off-line programming). Moreover, impedance control can be activated in free space during approach motion. Thus, it can be applied for the transition to and from the constraint motion, without specific control-switching algorithms.

Impedance control allows closed-loop position control in free space, while in contact with rigid environments, it offers force open-loop capabilities. Conversely, the force (admittance) control approach allows closed-loop force control capabilities in contact, but exhibits open-loop position control characteristics in free space. Therefore, the activation of force control in free space is only possible under specific circumstances. In general, however, a discontinuous control strategy is required for the transition from noncontact to contact motion phase or vice versa. The control structure change is done during the most critical phase when the manipulator is in contact with the environment. That represents a major drawback of force control. To cope with unexpected collisions, additional sensors (e.g., distance) have to be integrated into the control system. The fundamental superiority of force control is, however, that the interaction force is the result of the control action, rather than a result of deviation of the environment position and the chosen target impedance.

In Goldenberg's algorithm,[38] force control is closed around an internal impedance control loop. Desired force and force error are used to compute an equivalent desired relative motion of the end effector. Impedance control is included with the aim of achieving a suitable relationship between force and relative motion during contact. This is realized in the internal velocity loop by compensator gain adjustment to obtain target impedance. A similar reliable position-based force/impedance control scheme suitable for implementation in industrial robots has been proposed by Šurdilović and Kirchhof.[70] An external implicit force controller loop is closed around an internal position-based impedance controller (Figure 23.19). The main goal of the internal loop is to achieve target

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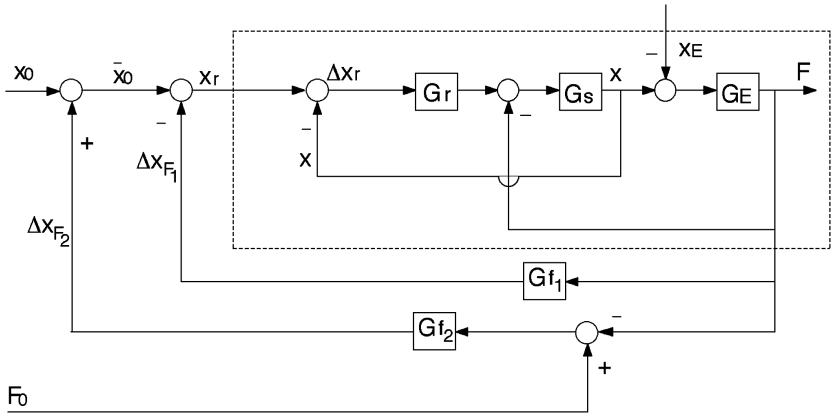

FIGURE 23.19 Position-based force/impedance control.

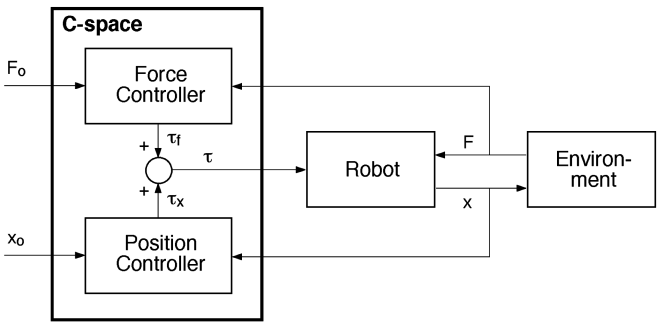

FIGURE 23.20 Parallel position/force control.

impedance while the external loop takes care of desired force realization. The selection between position (i.e., impedance) and force-controlled directions is not needed. Indeed impedance and force control affect all directions. A disproportion between motion and force planning is not critical in the control scheme (Figure 23.19), since the internal control loop behaves as a low stiffness target impedance system allowing relatively large differences between input position command and real robot position in the output. In the reverse, the internal loop in the implicit force control (Figure 23.18) is a very stiff position control, and the selection is inevitable.

Anderson and Spong[12] proposed an approach referred to as *hybrid impedance control* algorithm to control contact forces. The kernel part of the algorithm is Raibert and Craig's hybrid position/force control scheme, with the selection matrix applied to decompose position- and force-controlled subspaces. Both control parts use the feedback of contact force to realize desired system impedance (position-based and force-based impedance control) along each DOF.

A controller that combines an internal position control, a position-based impedance compensator, and a desired force feed forward was proposed by Mayeda et al.[71] The authors suggest that integral control actions be applied for both impedance (damping control) and force filters to ensure the compliance and the desired steady state force.

A different approach to position/force control, referred to as *parallel control* (Figure 23.20), has been proposed by Chiaverini and Sciavicco.[9] Contrary to the hybrid control, the key feature of the parallel approach is to have both force and position controls along the same task space direction without a selection mechanism. In general, both position and force cannot be effectively controlled in an uncertain environment. Therefore, the logical conflict between the position and force actions is managed by the dominance of the force control action over the position action along the constrained task direction

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where a force interaction is expected. The force control is designed to prevail over the position control in constrained motion directions. This means that force tracking is dominant in directions where an interaction with the environment is expected, while the position control loop allows compliance, i.e., a deviation from the nominal position in order to reach the desired forces. For this reason, the parallel control method can be considered a force/impedance control approach. The designed position tracking quality in constrained motion directions corresponds to target impedance behavior.

A set of sufficient local asymptotic stability conditions has been derived by Chiaverini et al.[72] for a parallel controller case consisting of a PD action on the position loop and a PI control in the force loop, together with gravity compensation and the desired force feed forward. Stability analysis and simulation results on an industrial robot are included. These conditions imply a relatively high damping (i.e., velocity gain) to ensure system stability.

23.6.4 Position/Force Control of Robots Interacting with Dynamic Environment

Vukobratović and Ekalo[8,33] established a unified approach to simultaneously control position and force in an environment with completely dynamic reactions. This fully dynamic approach to the control of robots interacting with dynamic environments will be presented in a condensed way. It will be assumed that $n = m$, where n is the number of robot DOFs and m is the number of contact force components. The general case in which $n > m$ has been considered by Vukobratović et al.[73]

When the environment does not possess displacements (DOFs) that are independent of robot motion, the environment dynamics in the robot coordinate space can be described by the model (23.9). Then the system (23.1 through 23.9) describes the dynamics of robot interaction with a dynamic environment. It is assumed in the contact case that all mentioned matrices and vectors are continuous functions and that the robot is in permanent unilateral contact with the environment.

In the case of contact with the environment, the robot control task can be described as motion along a programmed trajectory $\mathbf{q}_p(t)$ representing a twice continuous differentiable function, when a desired force of interaction $\mathbf{F}_p(t)$ acts between the robot and the environment. The nonlinear model programmed motion $\mathbf{q}_p(t)$ and desired force $\mathbf{F}_p(t)$ must satisfy the relation:

$$\begin{aligned} \mathbf{F_p}(t) &\equiv \mathbf{f}(\mathbf{q}_p(t), \dot{\mathbf{q}}_p(t), \ddot{\mathbf{q}}_p(t)) \\ \mathbf{f}(\mathbf{q}, \dot{\mathbf{q}}, \ddot{\mathbf{q}}) &= -(\mathbf{S}^{\mathbf{T}}(\mathbf{q}))^{-1}[\mathbf{M}(\mathbf{q})\ddot{\mathbf{q}} + \mathbf{L}(\mathbf{q}, \dot{\mathbf{q}})]. \end{aligned} \tag{23.51}$$

The control goal of robot interaction with a dynamic environment can be formulated by defining the control $\boldsymbol{\tau}(t)$ for $t \geq t_0$ that is to satisfy the target conditions:

$$\mathbf{q}(t) \to \mathbf{q_p}(t), \quad \mathbf{F}(t) \to \mathbf{F_p}(t), \quad \text{as} \quad t \to \infty \tag{23.52}$$

The two questions are addressed to the control design problem. Can we choose such a control law that, by satisfying preset robot motion quality, would enable the attainment of the control goals that satisfy the relation of Equation (23.52)? Is it possible to choose the control law in such a way as to ensure the preset quality of the robot interaction force and the attainment of the control goals? The answer to the first question is quite simple:[8,33] the inverse dynamics methods ensure that desired motion quality is achieved and at the same time guarantee that the interaction force is stable. The answer to the second question depends on the environment dynamics.

The task of stabilizing the programmed interaction force $(PFI)\mathbf{F}_p(t)$ can be posed by considering a family of transient responses with respect to force in the form $\boldsymbol{\mu} = \mathbf{F}(t) - \mathbf{F_p}(t)$ and by choosing a continuous vector function $\mathbf{Q}$ $(\mathbf{Q}(0) = 0)$ of dimension n, such that the asymptotic stability as a whole is ensured for the trivial solution of $\boldsymbol{\mu}(t) \equiv 0$.

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Let us consider pure force control according to the assumption that $m = n$, i.e., when the number of the contact force components is equal to the number of the powered DOFs of the robot. For convenience, when describing the quality of transient response perturbation force dynamics, $\dot{\boldsymbol{\mu}} = \mathbf{Q}(\mu)$, we shall use an equivalent relation of the form:

$$\dot{\boldsymbol{\mu}}(t) = \boldsymbol{\mu}_0 + \int_{t_0}^{t} \mathbf{Q}(\mu(\omega))d\omega. \tag{23.53}$$

With no loss in generality, we can adopt $\boldsymbol{\mu}_0 \equiv 0$, because the stabilization of $\boldsymbol{\mu}$ in the sense of preset quality Equation (23.53) directs stabilization according to the preset quality $\dot{\boldsymbol{\mu}} = \mathbf{Q}(\mu)$ independently from the value of $\boldsymbol{\mu}_0$.

Let us consider only one of the possible control laws with the feedback loops with respect to $\mathbf{q}$, $\dot{\mathbf{q}}$, and $\mathbf{F}$ of the form[8,33]

$$\boldsymbol{\tau} = \mathbf{H}(\mathrm{q})\mathbf{M}^{-1}(\mathrm{q})\left\{-\mathbf{L}(\mathrm{q},\dot{\mathrm{q}}) + \mathbf{S}^{T}(\mathrm{q})\left[\mathbf{F}_{\mathbf{p}} + \int_{t_0}^{t} \mathbf{Q}(\mu(\omega))\mathrm{d}\omega\right]\right\} + \mathbf{h}(\mathrm{q},\dot{\mathrm{q}}) + \mathbf{g}(\mathrm{q}) - \mathbf{J}^{\mathrm{T}}(\mathrm{q})\mathbf{F}. \tag{23.54}$$

By applying this control law to the robot dynamics model Equation (23.1) we obtain the following law of robot operating in contact with the environment:

$$\mathbf{M}(q)\ddot{\mathbf{q}} + \mathbf{L}(\mathrm{q},\dot{\mathrm{q}}) = \mathbf{S}^{\mathrm{T}}(q)\left(\mathbf{F}_{\mathbf{p}} + \int_{\mathbf{t_0}}^{\mathbf{t}} \mathbf{Q}(\mu(\omega))\mathrm{d}\omega\right)$$

Taking into account the environment dynamics model Equation (23.9), we obtain the following closed-form control system:

$$\mathbf{S}^{\mathrm{T}}(q)\left(\boldsymbol{\mu}(t) - \int_{\mathbf{t_0}}^{\mathbf{t}} \mathbf{Q}(\mu(\omega))\mathbf{d}\omega\right) = \mathbf{0} \tag{23.55}$$

and, because $rank(S) = n$, (23.55) is equivalent to: $\boldsymbol{\mu}(t) = \int_{t_0}^{t} \mathbf{Q}(\mu(\omega))d\omega$, from which $\dot{\boldsymbol{\mu}}(t) = \mathbf{Q}(\mu(\omega))$ follows directly. In this way, the control law (23.54) ensures the desired quality of stabilization of $(PFI)F_p(t)$.

The stability of the real motion (position) when asymptotic stability of the contact force is fulfilled has been considered.[8,33,89–91] Sufficient conditions for contrained motion stability based on the generalized Lyapunov's stability theorem in the first approximation of the system with perturbation have been derived. The theorem conditionally defines the internal stability properties of the environment because the fulfillment of stability conditions depends in general not only on environment dynamics but also on the nature of the programmed motion.

23.7 Contact Stability and Transition

The types of contact tasks may vary substantially in relation to specific requirements, but in all cases of performing a contact task the robot must perform three kinds of motions:

- *Gross motion*, related to movement in free space (free motion mode)
- *Compliant* or *fine* motion, related to movement constrained by environment
- *Transition motion*, representing all passing phases between free and compliant motion

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The contact transition can be considered stable if the contact is not lost after the manipulator meets the environment. A stable contact transition can be characterized by nonzero force (after contact is detected), positive penetration of manipulator end point into environment, nonappearance of bouncing, etc. The most critical issue in transition control is initial impact against a stiff environment. A stable controller should ensure the passage through the transition phase and maintain contact until all impact energy has been absorbed.

In most of the proposed control algorithms, instability occurs when the contact between end effector and environment is stiff. However, the investigations were primarily concerned with the question of *coupled stability* (i.e., will the robot remain stable when it is interconnected with the environment?) of robots and the environment under various control algorithms, while assuming the manipulator initially is and remains in contact with environment. Surprisingly, relatively little research has addressed the problem of *contact transition stability* (i.e., will the robot during transition from free to contact motion establish a continuous contact with the environment without multiple impacts?) which is most fundamental for performing contact tasks. The contact transition stability problem is important for both unilateral (force) and bilateral (geometric) constraints. A bilateral constraint is usually achieved by closing the gripper, due to position misalignment usually resulting from unilateral contact between gripper jaws and grasping object.

In *impedance control*, contact stability issues have mainly been considered based on simplified models of interaction between a target impedance system and the environment. Colgate and Hogan[74] defined necessary and sufficient conditions to ensure the stability of a linear robotic system coupled to a linear environment. The authors applied the network theory to describe the manipulator- and environment-interactive behavior at the equilibrium point. For the coupled interactive system described by the linear models, the equilibrium is defined by:

$$\begin{aligned}
\mathbf{p}^* &= \mathbf{p}(t; t \to \infty) = \mathbf{x}^* - \mathbf{x}_e \\
\mathbf{p}_0^* &= \mathbf{p}_0(t; t \to \infty) = \mathbf{x}_0^* - \mathbf{x}_e \\
\mathbf{e}^* &= \mathbf{e}(t; t \to \infty) = \mathbf{p}_0^* - \mathbf{p}^* = \mathbf{x}_0^* - \mathbf{x}^* \\
\mathbf{F}^* &= \mathbf{F}(t; t \to \infty)
\end{aligned} \tag{23.56}$$

where $\mathbf{p}_0 = \mathbf{x}_0 - \mathbf{x}_e$ and $\mathbf{p} = \mathbf{x} - \mathbf{x}_e$ denote *nominal penetration*, expressing a position planning failure due to tolerances, a desired entry into the environment, and *actual robot penetration*, respectively. For the adopted linear target impedance and environment models defined by Equations (23.14) and (23.11) respectively, these equilibriums can be expressed as:

$$\begin{aligned}
\mathbf{F}^* &= \left[\mathbf{I} + \mathbf{G}_e(0)\hat{\mathbf{G}}_t^{-1}(0)\right]^{-1}\mathbf{G}_e(0)\mathbf{p}_0^* = \left[\mathbf{I} + \mathbf{K}_e\mathbf{K}_t^{-1}\right]^{-1}\mathbf{K}_e\mathbf{p}_0^* \\
\mathbf{p}^* &= \left[\mathbf{I} + \mathbf{K}_e\mathbf{K}_t^{-1}\right]^{-1}\mathbf{p}_0^* \\
\mathbf{e}^* &= \left[\mathbf{I} + \mathbf{K}_e\mathbf{K}_t^{-1}\right]^{-1}\mathbf{K}_e\mathbf{K}_t^{-1}\mathbf{p}_0^*
\end{aligned} \tag{23.57}$$

Expressing the essential impedance control characteristics, interaction force **F**, penetration **p**, and position error **e,** in terms of nominal penetration are useful for the analysis of both coupled and contact transition stability.[53] During contact establishment, $\mathbf{p}_0(t)$ is a positive monotone-increasing function. In a passive stationary environment, two time-invariant networks coupled along interaction ports (Figure 23.21) can represent the interactive model around the equilibrium $\mathbf{p}_0(\infty) = \mathbf{p}_0^*$. The coupling makes the velocities of the robot and the environment at contact point equal, while the forces acting upon the robot and the environment have opposite activities (action

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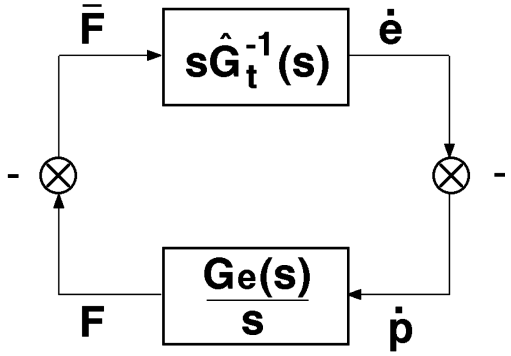

FIGURE 23.21 Robot/environment interaction model.

and reaction). If the environmental transfer matrix $\mathbf{G}_e(s)/s$ is positive real, representing a passive Hamiltonian environment, then a necessary and sufficient condition to ensure stability of a linearized robotic control system is that the *realized admittance* $s\mathbf{G}_t^{-1}(s)$ be *positive real*.[74] In other words, it should represent the driving point impedance of a passive network. In a SISO system, the *coupled stability* has been proven by using the Nyquist criterion and the positive real transfer function that has a limited phase of ± 90°.[74] It is then relatively easy to prove that the mapping of the Nyquist contour of a positive real environmental impedance $\mathbf{G}_e(s)/s$ through an also positive real admittance $s\hat{\mathbf{G}}_t^{-1}(s)$, altering the phase by ± 90° and changing the magnitude by a factor 0 to ∞, provides a stable system, i.e., a stable Nyquist plot of the open-loop coupled system transfer function.

The system *passivity concept* provides a relatively simple test for the assessment of coupled system stability. Only the passivity of the environment can be proven without accurate knowledge of parameters. Assuming that the ideal target impedance response Equation (23.15) is realized, the passivity of target admittance $s\mathbf{G}_t^{-1}(s)$ implies positive definite matrices $\mathbf{M}_t$, $\mathbf{B}_t$, and $\mathbf{K}_t$, and consequently, the closed-loop system should be stable in contact with any passive environment to which it is directly coupled. The explicit design of a positive-real robot control system, however, may become cumbersome.[75] Moreover, various practical control implementation effects, including computational time delay, sampling effects, and unmodeled dynamics (e.g., high order actuator and arm dynamic effects), may result in a nonpassive real impedance control response.[75]

The above stability results can be extended to nearly passive control systems. However, a passive environment can destabilize the coupled system. To simplify coupled stability analysis, Colgate and Hogan[74] used *worst* or *most destabilizing environment* to denote the most critical environment for coupled system stability. Such environmental impedance $\mathbf{G}_e(s)/s$ shapes the Nyquist contour of $s\hat{\mathbf{G}}_t^{-1}(s)$ by minimizing the distance from the critical point –1 to the nearest point on the Nyquist plot of the loop transfer function $\mathbf{G}_e(s)\mathbf{G}_t^{-1}(s)$. Since the driving point impedance of simple passive environmental models, such as mass or spring (M_e/s and sK_e), performs the maximum rotation in the Nyquist plane, the authors found that the *worst passive environment* for coupled stability consists of a set of *pure masses and springs*. If both the environment and the realized admittance are stable, the coupled stability of the interactive system in Figure 23.21 can also be assessed by means of the *small gain theorem* by which a feedback loop composed of stable operators will certainly remain stable if the product of all operator gains is smaller than unity:

$$\left\|\mathbf{G}_e(j\omega)\hat{\mathbf{G}}_t^{-1}(j\omega)\right\|_\infty < 1 \tag{23.58}$$

The small gain theorem provides a general law, valid for continuous- or discrete-time, SISO and MIMO, and linear and nonlinear systems. It is also the convergence criterion used in many iterative

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processes. Furthermore, the norm inequality criterion (Equation 23.58) can easily be extended to maintain the uncertainties in the target system and environment models.

However, the small gain theorem only provides sufficient stability conditions, which in many cases are too conservative to be of much use in practical contact tasks. For example, assuming that ideal second-order target impedance has been achieved, the condition (Equation 23.58) implies the admissible target stiffness to be $K_t \geq K_e$ to ensure a stable interaction. In stiff environments, this has no practical relevance. This result is similar to the stability analysis performed by Kazerooni et al.[16] The established interaction stability criterion practically implies that the gain of feedback compensator (i.e., the target admittance) should be limited by the magnitude of sum of environmental admittance and robot position control sensitivity. For a SISO system, this imposes, in the steady state:

$$K_t \geq \min\left(K_p, K_e\right) \tag{23.59}$$

In direct drive robotic systems with significantly less position control stiffness (due to elimination of the transmission) than in industrial robots, this condition might provide reliable target models for practical tasks. The sufficiency of stability condition (Equation 23.59) has experimentally been demonstrated on a lightweight direct drive University of Minnesota robot. However, from the viewpoint of industrial robot performance, this condition is conservative and practically useless. In industrial robots, with stiff servo gains (e.g., position control gains usually have the order 10^6 N/m), the value is $K_p > K_e$ and the above condition also requires the target stiffness to be higher than the environmental one. Moreover, no target model, i.e., the compliance feedback compensator G_f (Figure 23.11), can be found to enable interaction with an infinitely rigid environment ($K_e \to \infty$). Therefore, one of the main conclusions in Kazerooni et al.[16] pointed out the need for intrinsic compliance either in the robot or in the environment to maintain interactive stability.

The *coupled stability* analysis around the equilibrium point cannot be applied for the analysis of *contact transition stability*, and this represents a fundamental contact control task problem. Reliable criteria ensuring contact stability of a linearized robotic control system under impedance control during transition from the free space to a unilateral contact within a passive environment has been established by Šurdilović.[42] The contact transition stability conditions require interaction force, i.e., actual penetration to be nonnegative $\mathbf{p}(t) = \mathbf{x} - \mathbf{x}_e \geq 0$, or the position deviation to be less than the nominal penetration $\mathbf{e}(t) \leq \mathbf{p}_0(t)$ i.e.,

$$\frac{\left|\mathbf{e}(t)\right|}{\left|\mathbf{p}_0(t)\right|} = \frac{\left|\mathbf{p}_0(t) - \mathbf{p}(t)\right|}{\left|\mathbf{p}_0(t)\right|} = \frac{\left|\mathbf{x}_0(t) - \mathbf{x}(t)\right|}{\left|\mathbf{x}_0(t) - \mathbf{x}_e\right|} \leq 1 \tag{23.60}$$

This relation implies the actual end effector position during a stable contact transition will always be located between the position of environment and the nominal position. Since this contact stability condition is based on a simple geometric consideration, it is referred to as the *geometric criterion.*[42] This criterion theoretically can be applied in cases when the actual position overshoots the nominal one, i.e., when $\mathbf{p} > \mathbf{p}_0$, which provides a negative position error. However, in a contact with an industrial robot with a realistic stiff environment, the actual motion is nearly stopped by the resistant force and impedance control effects, so this case has no practical relevance. The advantage of the geometric criterion is that it compares two time signals. The norm comparison offers possibilities to apply relatively simple and efficient system theory formalisms for contact stability analysis. This criterion has been utilized[76] to derive the *robust contact stability* condition ensuring both coupled and contact transition stability based on:

$$\sup \frac{\left\|\mathbf{e}(t)\right\|_2}{\left\|\mathbf{p}_0(t)\right\|_2} < \left\|\mathbf{W}(s)\left(\mathbf{I} + \mathbf{G}_e^{-1}(s)\mathbf{G}_t(s)\right)^{-1}\right\|_\infty \leq 1 \tag{23.61}$$

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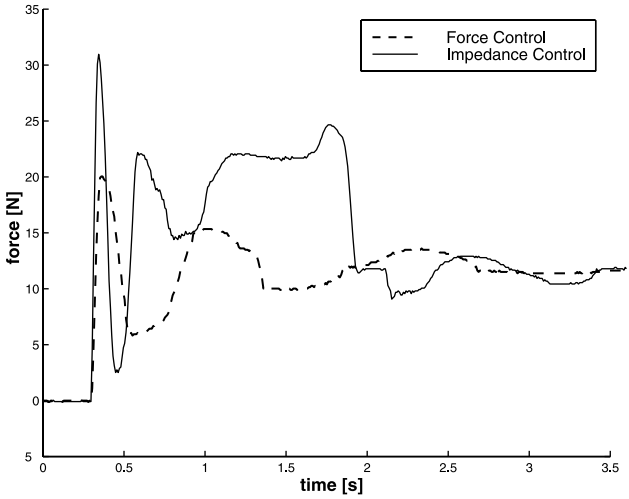

FIGURE 23.22 Performance comparison: impedance vs. implicit hybrid control.

where stable weighting transfer function matrix $\mathbf{W}(s)$ describes uncertainties of the environmental model and the target impedance realization. In a SISO system, this condition implies:

$$\xi_t \geq \frac{1}{2}\left(\sqrt{1+2\kappa}-1\right) \tag{23.62}$$

where $\xi_t = B_t / 2\sqrt{M_t K_t}$ and $\kappa = K_e / K_t$ are target damping and stiffness ratios, respectively. However, in spite of an effective and simple formulation, this criterion ensures *sufficient* contact stability conditions, but not the *necessary* ones. Consequently, the obtained contact stability indices might be conservative. It should be mentioned that the damping ratio bound Equation (23.62) is still less than the usually applied *dominant real pole* solution[77] imposing $\xi_t \geq \sqrt{1+\kappa}$. A very important advantage of the input/output criterion Equation (23.61) is that it can be applied for both continuous and discrete systems including the time lags. The control time lag has been identified by Šurdilović[76] as the critical destabilizing contact transition effect. In general, a retarded system requires a significantly higher amount of damping to stabilize the transition process with delayed force signals.

Typical transition experimental results in position-based impedance and force control during contact with a stationary environment are presented in Figure 23.22.[42] The force transition in hybrid control is characterized by lower overshoots. The reason is that force control represents an explicit aspect of hybrid control that is achieved by appropriate control structure and design. In the impedance control, however, the aim is to passively modify a preplanned motion in accordance with the interaction forces. Therefore, the force transition in the impedance control is greatly measured and influenced by selected target impedance parameters and nominal motion.[42]

Lawrence[14] analyzed the destabilizing influence of time delays on impedance control performance. Vossoughi and Donath[78] investigated the influence of nonlinear friction effects on the performance of an impedance-controlled hand. High position control gain (or integral gain) leads to limit cycles due to friction/stiction effects.

In contrast to the impedance control algorithms that provide the same control structure for the three motion phases, the transition to and from contact motion is usually based on discontinuous control in force control schemes. The change of the control strategy from position control to force control occurs in the free space, and the transition is realized in the force control mode after contact is established. Most force control algorithms execute the transition control in the *force mode*. The reason is that the impact force can be very large, especially when due to high approach velocities and delay in a stiff position controller. One method to reduce impact is to use a soft force sensor,[79]

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i.e., passive compliance, but this reduces the position accuracy during position control. The underlying idea of most methods concerned with the impact problem is to increase damping in the collision direction.[22] Assuming a simplified stiffness model of environment, the damping effect can be achieved either by force derivatives or approach velocity feedbacks. However, both methods have practical limits. The force signals are usually noisy and the derivation is inaccurate. Qian and De Schutter[80] proposed low-pass sensor filtering and nonlinear damping to cope with the transition problem. The velocity sensing is also not reliable at slow approach motion before contact.

Moreover, in a stiff environment, relatively fast oscillations in force and velocity can cause instability due to time (phase) lags between sensing and control action. These difficulties have been recently addressed in several works aimed at designing a stable force controller without velocity measurement,[81] and without end effector contact force sensing,[82] when the system dynamics is well known. However, these innovative schemes are complex to implement and require further tests.

Independent of the active damping method, the transition control based on the force mode generally requires some modification of control strategy or gains before and after impact. For example, in integral explicit force control, the force error integration in the free space causes the robot to accelerate in the force direction. Hence, the maximum impact velocity or integration wind-up should be limited in the free space. In implicit integral force control, a constant force error corresponds to a constant position correction velocity, but usually the different gains should be used in the free space and during contact to achieve desired system performance. The gains synthesized for stiff contact provide very slow free motion, while contact stability is jeopardized in the opposite case.

In the second transition control concept, the approach phase is realized in the *position control mode*; after contact is established, the control is switched to force control mode. Numerous discontinuous transition control algorithms have recently been tested. By treating the discontinuous controller as an entire generalized system, Mills and Lokhorst[83] proposed a discontinuous control scheme that guarantees global asymptotic stability of the closed-loop system, asymptotic trajectory tracking of position and force inputs, and reestablishment of contact after an inadvertent loss.

Wu et al.[84] proposed the addition of a positive acceleration feedback to the force control in the impact direction. In addition, a switching control strategy is introduced to eliminate unexpected bouncing. A similar control strategy for the transition problem in both force and impedance control has been developed by Volpe and Khosla.[85] They recommended use of positive force feedback during transition, and integral force control after stable contact is established. A force-regulated switch triggers the transition from position control to impact control. For the further switch to integral force control, several options were proposed. Based on the equivalency of force and impedance control, the authors established the transition stability condition for the impedance control-imposing ratio (robot inertia through target inertia) at less than one. Using a direct drive robot at very high impact velocity (0.7 m/s) with a relatively stiff environment (10^4 N/m), the authors demonstrated the reliability of established criteria. However, these results are not applicable to industrial robots, with high Cartesian inertia levels (> 500 kg), very stiff position controllers, and time lags that cause switching algorithms to be critical.

Gorinevski et al.[86] examined the transition problem of both impedance and general force control during contact with stationary and dynamic environments. They tested linear control and sliding mode control. The influence of several effects, such as time delay and elasticity of robot end effector, transmissions and mechanical structure, on the contact stability has been examined. The contact stability criteria for single and two DOF systems are derived in the explicit closed form in terms of control gains and limits on robot and environments velocities.

Several authors consider transition control a short-impulse dynamic problem. This model is valid for very fast systems (e.g., micro–macro manipulators), but is seldom used in practice. In industrial robotic systems, the transition problem can be accurately analyzed in a finite time period. Most industrial control systems still do not provide mechanisms to control short-impulse impact effects.

McClamroch and Wang[32] emphasized the importance of constraints in constrained dynamics. They presented global conditions for tracking based on a modified computed torque and local conditions for

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feedback stabilization using a linear controller. The closed-loop properties of force disturbances, dynamics in the force feedback loops, and uncertainties in constrained functions were also investigated. Eppinger and Seering[87] have studied the influence of unmodeled dynamics on contact task stability, introducing additional (elastic) degrees of freedom of both the robot and the environment.

A treatment of the contact stability, considering the environment as a nonlinear dynamic system is given by Hogan.[34] It is shown that if the impedance control is applied, enabling the robot to be asymptotically stable in free space, the robot interacting with the environment is a passive system and is stable in isolation. However, the conclusion is valid only if the robot in contact is at rest and for this reason the result cannot be considered complete. The stability issue, i.e., the establishment of the conditions under which a particular control law guarantees the stability of the robot in contact with the environment, is of great importance.

Vukobratović and Ekalo,[8,33] and Vukobratović[88] focused attention on control laws that simultaneously stabilize the motion of the robot and the forces of its interaction with a dynamic environment, ensuring the exponential stability of the closed-loop systems (based on the analysis of a complete dynamic model of the robot and the dynamic environment). The papers formulate conditions ensuring an asymptotically stable position of the system in the first approximation (local stability). The character of the position stability depends particularly on the nature of the programmed (desired) motion. In spite of sufficient conditions of the linearized system, asymptotic stability is conservative, and the dynamic character of the interaction of the environment with the robot can lead to positional instability. This problem deserves the full attention of researchers and designers of robot controllers dedicated to diverse contact tasks. This linear analysis provides very important criterion that must be fulfilled by any force-based law. However, the model uncertainties representing a crucial problem in control of robots interacting with a dynamic environment still have not been appropriately addressed. Therefore, it can be difficult to achieve the asymptotic (exponential) stability of the system (unless robust control laws including factors for compensationg these perturbations and uncertainties are used). Inaccuracies of robot and environment dynamic models and dynamic control robustness have been considered by Ekalo and Vukobratović.[89-91]

Problems arising from parameter uncertainties may also be resolved by applying knowledge-based techniques.[92] Taking into account external perturbations and model uncertainties, it may be difficult to achieve asymptotic (exponential) stability. Therefore, it is of practical interest to require less restrictive stability conditions, i.e., to consider the so-called practical stability of the system. An approach to analysis of the practical stability of manipulation robots interacting with a dynamic environment based on a centralized model of the system is presented by Stokić and Vukobratorić.[93] The test conditions for practical stability of the robot interacting with dynamic environment are recently derived.[93,94] The presented tests might be too conservative due to the number of linearizations (approximations) made. More refined approximations by, e.g., taking into account possible dependencies of the model elements (matrix of inertia, Coriolis forces, Jacobian matrix, etc.) on the parameters, may lead to less conservative tests.

23.8 Synthesis of Impedance Control at Higher Control Levels

Although several sophisticated control strategies have been proposed, the numbers of advanced robotic contact task applications remain insignificant. The reason is that most new concepts concern particular problems and the integration of the required algorithms and control concepts is tedious. Most of the studies on impedance and force control relate to servo control. Except for the seminal works on compliance control,[1,48] contact task planning and programming issues have been somewhat neglected in the research studies.

The next section briefly addresses solving high-level impedance control problems in industrial robotic systems. The problems with impedance control motion planning and programming layers were investigated during the development of the new space robot control system (SPARCO),[95] in order to develop a completely integrated reliable impedance control system including control,

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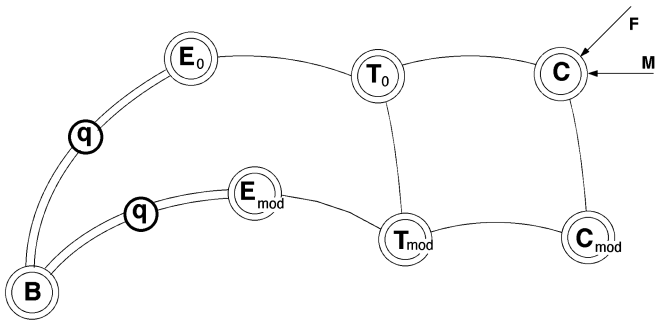

FIGURE 23.23 Compliance frame and position modification.

programming, and monitoring functions. Several control algorithms for the integration of a position-based impedance control scheme in conventional industrial robot control systems will be presented.

23.8.1 Compliance C-Frame

One of the most common approaches for word modeling (specification of robot and object positions) in robot programs is based on coordinate frames. Beside coordinate frames that are convenient for the programming of robot motion in the free space (e.g., robot base B, end point E, tool T frame, etc.), a compliance control includes two new frames, specific for compliant motion programming: force sensing S and compliance frame C. The S frame is a force sensor-specific frame in which the forces and torques are measured. This frame is commonly defined relative to the robot end point E. With respect to the C frame, the target impedance behavior (robot impedance reaction) is specified and controlled. Since the location of the C frame depends on the current task, we have chosen to specify the convenient C frame relative to task T frame (Figure 23.23) taking into account that the T frame is a variable selected to meet specific task motion requirements. Usually the desired robot position specifies the location of the T frame (specified relative to the E frame, e.g., tip of the tool) with respect to an object frame.

The basic specification of compliance control required for the implementation addresses both the definition of C frame location with respect to the tool frame and the selection of appropriate target impedance parameters in the C frame based on the geometric model (Figure 23.7) for the specific task. A set of associated robot programming commands is needed to handle this specification in the robot program.

A specific problem in the position-based impedance control is the computation of the position correction $\Delta\mathbf{x}_F$ (Figure 23.11) corresponding to the interaction force. An obvious approach is to compute this modification in the C frame where the compliance behavior is specified. While the computation of $\Delta\mathbf{x}_F$ for the translational DOFs is straightforward, there are several possibilities for managing the rotational difference dependent on the representation of orientation. The description of orientation affects the relationship between the position displacement $\mathbf{x}_0 - \mathbf{x} = \mathbf{p}_0 - \mathbf{p}$ and the forces/torques. The form of the target impedance matrices (Equation 23.14) in Cartesian space also depends on rotation representation. The SPARCO control system approach[95,96] utilizes the angle axis orientation description in the C frame. The compliance model (Figure 23.7) is based on ideally decoupled translational and rotational stiffness (impedance). This is indeed an idealized representation. As demonstrated by Lonari,[97] a point at which translational and rotational elasticity are completely decoupled does not always exist for a compliantly supported spatial rigid body. The point at which they are maximally decoupled is referred to as the *center of stiffness*. The simple SPARCO approach allows the rotational impedance parameters to be directly related to the task geometry described in the C frame, i.e., in the tool-frame T_0. The selection of the C frame location is based on geometric task analysis in T_0 and consideration of the force/displacement equilibrium.[96]

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Additional possible rotation description models for compliance control are presented by Caccavale et al.[98] Several authors considered achieving target stiffness with linear and rotational springs,[99] spring systems,[100] and serial elastic mechanisms.[101] Besides the synthesis of passive compliance devices, these works are relevant for the better understanding of spatial compliant behavior in robot contact interaction tasks. A more general compliance planning (impedance selection) approach has recently been proposed by Fasse and Broenink.[102] This approach is based on *spatial affine* presentation of compliance described by sets of geometrical and nongeometrical parameters independent of robot/object configuration. A spatially affine family of compliances provides invariant wrenches with respect to the rigid body transformation. This simplifies the selection of the target impedance.

23.8.2 Operating Modes

Additional control functions and commands are required to manage dynamic communication between the basic position control system and the impedance control module. This section describes impedance control functions that support programming compliance control applications.

Although the impedance control feedback is activated and deactivated by contact with the environment (Figure 23.11), the mechanisms must functionally manage the activation of the control modules and functions. It is convenient to introduce the following impedance control operating modes:

- *Stopped mode*, with no impedance control functions performed. This mode corresponds to conventional position control systems.
- *Monitoring mode*, performing monitoring functions in real control time such as monitoring sensor and process force/torque limits, checking position correction bounds, contact check, collision detection, end effector monitoring functions, etc.
- *Running mode*, in which monitoring and exteroceptive control functions (computation of impedance control loop) are executed at each sampling interval.

In the initial stopped status, the impedance control can be initialized by selecting the sensor type and transferring the control and machine data to the local control functions. Before activating the impedance control functions, the status is changed to monitoring mode. This mode allows a change to task-dependent control parameters such as tool and compliance frame locations, impedance gains, contact force limits, and desired force still in contact with the environment, without deactivating the external control. An algorithm, referred to as the *relax* control function,[95] has been used to meet the conditions for a continuous change of impedance control parameters.

Once the running mode has been started, all subsequent robot motions are automatically modified by the corrections corresponding to the force and selected impedance target gains. Any transition to the monitoring or stopped modes automatically resets position correction offset (position synchronization) by replacing the nominal robot position in the interpolator by the actual current robot position. This allows the robot motion to continue in the position control mode starting from the actual position.

23.8.3 Change of Impedance Gains — Relax Function

Since the impedance control parameters define a desired target mechanical system, they should often be changed, depending on the current action (some actions, such as *insert,* require target impedance to be changed several times during execution) to meet action-specific requirements. The location of the compliant C frame in which the impedance is controlled must also be varied. The main problem with the parameter changes in a control system is achieving a continuous, transient switching (bumpless parameter change).

When the robot is in contact with the environment, any discontinuous parameter change can cause control chattering due to interruption of the impedance force/motion relationship, for example,

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by alteration of gains (i.e., variation of stiffness) or compliance frame location (change of force and torque components). The control gain switching can be especially critical in directions in which high stiffness level is replaced by low stiffness and vice versa. In free space, however, impedance parameter switching is not critical since the impedance feedback loop is inactive due to zero contact force.

The way to obtain bumpless parameter changes is to achieve similar contact conditions as in free space by reducing the interaction force to a minimum level while maintaining contact with the environment. This is realized by the relax built-in program language functions consisting of the following steps:

Step 1: Switch the impedance control to the monitoring mode and reset position correction offset.
Step 2: Settle the damping control gains (target stiffness is zero) in all C frame directions and desired force to zero.
Step 3: Switch the impedance control to the running mode.
Step 4: Due to contact force, the robot moves until the given small force threshold is reached in all directions during a selected time period.
Step 5: Switch the impedance control again to the monitoring and reset offset and initial impedance gains.

The main issue of the *apply-force* function is to realize a specified steady state force. In impedance control, the force can generally be regulated only in an open loop by proprietary generation of robot motion in accordance with the selected target system. However, this approach requires accurate knowledge of contact point location, and is sensitive to disturbances (e.g., friction forces). In the SPARCO-implemented approach, a constant force is achieved in the closed loop based on the damping control that provides a correction velocity proportional to the error between actual and desired forces (integral force control). Thus, the robot corrects its position in corresponding directions until the force error becomes less than the given threshold.

23.8.4 Impedance Control Commands

Program instructions are required to allow the programmer to manage impedance control parameters and monitor and handle various contact exceptions. These instructions select impedance control gains, read the contact force, check the force limits and contact with the environment, and indicate when the desired force is achieved. In conjunction with the standard robot programming language commands, exception handling, and motion synchronization mechanisms, these devices provide a powerful framework for programming complex impedance control algorithms. These new commands are specified by Šurdilović.[95]

Setting impedance control parameters is done in an implicit manner by using understandable linguistic descriptions using high, medium, or low attributes in conjunction with target impedance or damping models. To each description case a set of gains is designed for SPARCO applications in a CAT environment and put in a look-up table initialized during system setup. The user can select an individual set of control gains that should be read from a specified file. A built-in function is provided to facilitate the selection of user gains (set/user/gf). The control gains for the impedance controller are put in the system memory (look-up table).

23.8.5 Control Algorithms

A major question in using sensor-based robot control is how to apply sensory information to perform a given task in the presence of uncertainty and errors. This requires new algorithms to be developed to predict and detect various events and generate corresponding reliable robot actions. Facilitating the use of sensory information, robot-programming language should provide the mechanisms to

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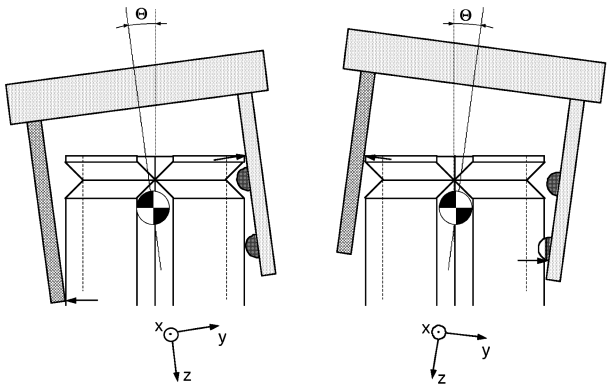

FIGURE 23.24 Grasping using impedance effect.

easily access sensory information and use it to control the robot. Two examples are presented to illustrate the practical contact control task using new impedance control functions and commands.

23.8.5.1 Grasping

Nominal relative configuration (position) between end effector and object before gripper closing with relative high accuracy must be achieved to grasp a fixed object properly. The grasping algorithm based on impedance control allows the gripper to self-align to the fixed objects to be grasped, and thus compensates for inaccuracies in environment and robot control.
The following basic specification of the impedance control parameters is required to meet the grasping requirement:

- The compliance C Frame is located approximately at the gripper middle point between the hemispheres (Figure 23.24) used to support the gripper self-alignment along grooves, based on the impedance control effect.
- Low impedance is selected in each direction.

To achieve a good centralized grasp (the compliance center is located near the grapple fixture axis), internal grasp forces are approximately balanced, and the resulting torque causes a rotation about the center of compliance. In an opposite case, lateral misplacements are dominant, causing a one-sided contact. The lateral force and corresponding torque around the compliance center cause the robot to correct initial position and orientation and both jaws grasp the object (Figure 23.24). The robot moves until the desired internally stable grasp is achieved. (The jaw hemispheres and grapple fixture notches in conjunction with contact friction prevent further motion.

23.8.5.2 Insertion

Industrial programmers have experience with the insertion function using RCC passive elements. The impedance control provides a similar approach. Moreover, the control system capabilities that change impedance control gains or compliance frames in various task phases also provide a programmable compliance device.

The insertion (Figure 23.25) control algorithm requires three procedures: engagement, insertion, and termination. The selection of impedance control gains in these phases is shown in (Figure 23.26). Engagement requires that part chamfers meet and slide past one another. The following impedance control specifications apply to the engagement phase:

- The C frame should be located near interacting force directions (on the peg top).
- The insertion (i.e., engagement) motion consists of a linear displacement in the positive z direction along the hole axis. The target position is chosen below the nominal front surfaces (below the ends of the chamfers).

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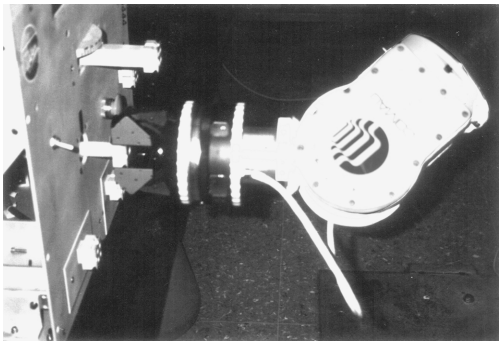

FIGURE 23.25 Insert task.

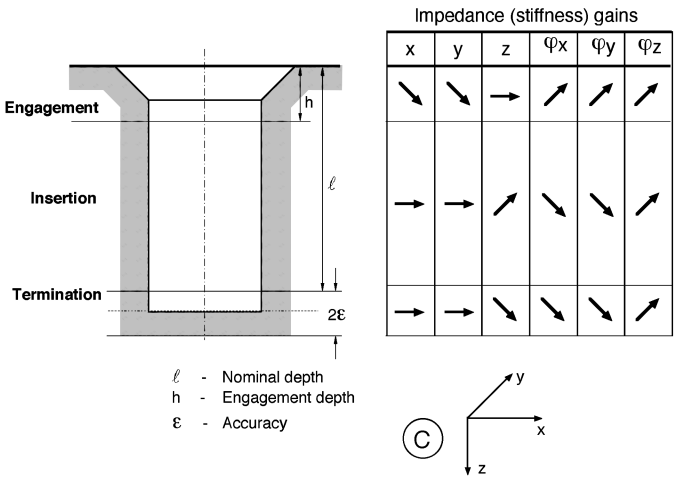

FIGURE 23.26 Impedance gains selection.

Determining a medium stiffness (Figure 23.26) in the z direction during engagement should take into account that the robot motion is unconstrained in this direction. To slide along the chamfers, the stiffness in lateral directions (x, y) must be less than the axial stiffness, causing a faster misalignment than encountering the surface (the lateral force/stiffness behavior serves as a cue to the desired corrective motion). This also reduces contact forces (Figure 23.26), allowing the peg to cope easily with the friction. A high rotational stiffness is required, taking into account the goal to compensate for lateral misalignment only, without introducing unwanted rotation.

After engagement depth is reached, the insertion procedure is started. The lateral rotation impedance (stiffness) around the x and y C frame directions is switched (after relaxing the contact) to low to compensate for the rotation error. This impedance in the insertion direction (z) along the hole is set to medium since the robot motion is unconstrained in this direction and is required to compensate for the disturbing friction forces between the peg and hole during insertion. The insertion phase ends when a termination pose in front of the peg bottom is reached. It is selected dependent on estimated position tolerances to avoid contact with the bottom of the hole. The C frame should be located near the middle point of the hole to relax the peg (similar to Figure 23.24) and change gains for the next phase. The termination phase algorithms are dependent on the termination strategy (governed by position, external signal, or force). In each case the low impedance is selected in the insertion direction to avoid large contact forces due to inaccuracies.

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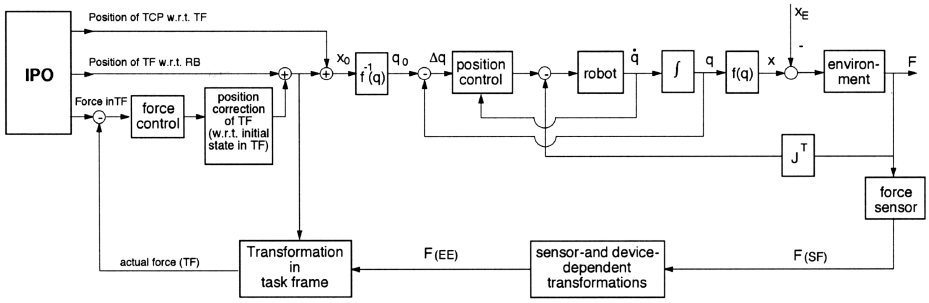

FIGURE 23.27 Integration of implicit hybrid control.

23.8.6 Implicit Force Control Integration

A practical method to integrate implicit force control and orthogonal decomposition in a position control system for robot manufacturing applications (e.g., deburring) was proposed by Lonari.[97] The hybrid control integration is realized at motion interpolation level (Figure 23.27). In order to decompose position and force control DOF, two virtual kinematic structures in Cartesian space are assumed: the first driven by the position interpolator and the second obtaining the position commands (i.e., relative modifications) from the force control in the compliance i.e., task frame TF. The interpolator (IPO) generates the nominal position of the tool center point (TCP) in the position control DOF in the task frame. The integral implicit force control modifies the position of TF in force-controlled directions relative to its initial location at the robot reference frame (e.g., robot base frame, object frame) according to the force error. Superimposition of both positions produces the command for the internal position controller $\mathbf{x}_0$. Independent of modifications of the tool position and/or orientation in force direction (e.g., tool feed direction) based on interaction forces, it is possible to realize the desired motion in position-controlled directions, such as changing the tool clearance in toll directions etc.

23.9 Conclusion

During the past several years, compliant motion control has emerged as one of the most attractive and useful research areas in robotics. The control of constrained motion of robots is challenging and a successful solution will affect considerably use of robots in industry and increase their efficiency and productivity.

It may be of interest to indicate possible future investigation areas. Clear formulation and specification of hybrid control are required. Further simulation and experimental tests of recently proposed compliant motion control algorithms, such as parallel position force control, adaptive and variable structure algorithms, and, particularly, dynamic control of a robot interaction with a dynamic environment, are also of interest. Effort should also be devoted to solving the problem of contact task control where the uncertainties and nonlinear effects in the environment and the robotic system, such as friction, multipoint contact, elasticity, etc. must be considered. In impedance control, further advances are expected in adaptation of target impedance to complex task requirements. The compliant motion capability analysis of industrial robots and requirements for the next generation are of interest to designers. Robust control continues to be the focus of control design. Comparison of available algorithms, definition of benchmark tests, investigation of compliant control in uncertain and dynamic environments, examination of nonlinear effects in robot and environment dynamics, and solving control problems at higher control levels certainly deserve further computational/experimental studies.

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